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Biomechanics Cinematography Procedures for Vertical Force Measurements in Jogging

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Biomechanics Cinematography Procedures for Vertical Force Measurements in Jogging submitted by Jon Robert Kuntz in partial fulfilment of the requirements for the degree of Master of Science.

DEDICATION

To Mary

Whose understanding, inspiration, constant encouragement, and love made this entire "adventure" possible.

God bless you!

ABSTRACT

The purpose of this study was to develop a method utilizing biomechanics cinematography exclusively for determining the vertical force component of jogging. An attempt was made, via biomechanics cinematography, to reproduce the vertical force characteristics of jogging as recorded by a force platform. Synchronized records from cinematography of joggers in the sagittal plane and the analog force signal from a force platform were obtained.

Analysis of the direct force measurements were made using a PCB208A04 piezoelectric force transducer mounted in a force platform. When plotted graphically the force-time curves depicted the support phase of jogging. Two 16mm pin registered Photo Sonics 1PL cameras were used for the acquisition of cinematographic data. A Triad VR/100 pin registered film analyzer, Bendix Digitizing Board, and Hewlett Packard 9825B desk top computer were used for the analysis of acquired cinematographic records of the joggers. The cinematographic results were computed in three steps; the foot strike phase or impact phase, the mid-support phase, and the takeoff phase.

Results obtained indicated the total elapsed time for the support phase in jogging to have a mean value of 0.21 seconds. From direct force measurements, it was determined that the force-time curve has an initial peak of short time duration with a maximum measurement between 3.3

and 4.0 times the body weight of the subject. The initial peak was followed by a second peak which gradually descended to a force value of zero. The biomechanics cinematography procedures produced a force-time curve with similiar characteristics. It was determined that within the foot strike phase the cinematographical measurements differed from the force plate measurements by a mean of +100.7N. Within the mid-support phase the cinematographical measurements differed by a mean of -62.5N, and during the takeoff phase the cinematographical measurements differed by a mean of +27.9N. The magnitude of the overall mean error was found to be 6.2N.

ACKNOWLEDGEMENTS

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A special thank you is extended to my other committee members; Dr. E.W. Bedingfield, Dr. J. Kramer and Prof. G. Simonyi.

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CHAPTER I

STATEMENT OF THE PROBLEM

Introduction

The majority of the experimental biomechanics research on jogging has been limited to kinematics. Stride rate, stride length, angular displacements and temporal analyses are most prevalent. Considering the large number of participants in jogging, as a recreational and fitness activity, the present knowledge concerning the biomechanics of jogging is limited. This may in part be due to a lack of "on the field" or "real life" measurement capabilities as well as the high cost of precise force measurement instrumentation. In order to measure force generation during jogging outside a laboratory situation, biomechanics cinematography may be a useful procedure. However, as useful as it may be, precise and practical force measurement procedures through biomechanics cinematography have not been developed. Cinematography, a non-invasive technique, eliminates the need for any physical limitations or laboratory controlled experimental procedures for the acquisition of data. Through the use of cinematographical procedures, data is easily obtainable and if so desired,

without the subject's knowledge. This guarantees a true life performance as compared to one in which alternate experimental procedures could very easily cause the subject's performance to be unnatural. The present study was undertaken to attain a practical experimental procedure to determine vertical force parameters utilizing biomechanics cinematography.

Purpose

The purpose of this study was to develop a method for the calculation of the vertical force component of jogging through biomechanics cinematography. In particular, an attempt was made to reproduce the vertical force characteristics recorded by a force plate during jogging using cinematographical procedures.

Limitations

1. The accuracy in determining body segment parameters was limited to the accuracy of the Humanscale Anatomical Data (DIFFRIENT 1979) and the ability of the examiner in locating the proximal and distal end points of the body segments.
2. The accuracy inherent in cinematographical data acquistion and analysis could not be totally eliminated even though precautions were taken to minimize errors.

due to film graininess, optical distortion from the recording and projecting devices, and perspective error.

3. The use of a force platform, although level with the running surface, could have caused a loading error by the subjects being required to make contact on a specified area.
4. It was assumed that the motion occurred only in the sagittal plane.

Delimitations

1. The cinematographical analysis was restricted to a two dimensional analysis of motion in the sagittal plane.
2. The force plate data was restricted to the vertical force component.
3. Description of the cinematographical data was restricted to a sampling frequency of 25 frames per second from data obtained at 100 frames per second.
4. Description of the force plate data was restricted to a sampling frequency of 100 frames per second.

Definition of Terms

Biomechanics cinematography

The acquisition and subsequent analysis of data specific to biomechanics research through the use of cinematographical procedures and computer techniques.

Running

A form of locomotion, when in humans, the body is supported alternately by the two lower extremities with an air-borne phase between.

Jogging

A form of locomotion in which the gait is much slower than running, but faster than walking. (Walking is characterized by having no air-borne phase).

Stride

A measurement taken from the initial contact of one foot to the subsequent contact of the same foot.

Non-support phase

The period of a stride when the body is not in contact with the running surface. (A walking stride lacks a non-support phase).

Support phase

The period of a stride when either foot is in contact with the running surface. Each stride is composed of two support phases (i.e. right support phase and left support phase).

Foot strike phase

That period of the support phase from the initial contact to when the foot is firmly fixed or flat on the running surface.

Mid-support phase

That period of the support phase when the foot is firmly fixed until the instant the heel begins to rise off the surface. In the case of the force plate recordings, the mid-support phase begins at the lowest point reading after the initial peak. In the case of the biomechanics cinematography data, it begins at an assigned point in time from the initial contact of the foot.

Takeoff phase

That period of the support phase from the instant the heel begins to rise until the toes break contact with the running surface.

Phase-lock

An electronic system which ensures frame for frame synchronization of the film at any set frame rate of intermitent pin-registered high speed cameras.

CHAPTER II

REVIEW OF LITERATURE

This chapter deals with the available literature pertinent to this study. Much literature has been published concerning the various forms of human locomotion. However, relatively few attempts have been undertaken to determine various kinetic parameters of jogging. Included within this chapter are pertinent studies on temporal and spatial measurements, kinetics, and various force measuring devices specific to human gait analysis.

As early as 1930 studies were undertaken to determine scientifically various parameters of running. One of the pioneers of running mechanics, FENN (1930), reported the center of gravity within the body reached its maximum elevation the instant of takeoff and then continually fell through the flight period and into the support phase.

POWELL (1960) reported that in running, force was continually applied below the body until the body weight passed over the point of support. The height of the heel rise behind the runner was proportional to the force exerted and was a reaction to the power used.

SLOCUM et al (1962) discussed the distance spanned during the non-support period of running. It was reported that the non-support distance was greater than the support phase. It was also noted that this distance could be varied by the runner by the force exerted at takeoff. However, any attempt to increase the float phase was cancelled by increased ground resistance at foot strike.

In another article published six years later, SLOCUM et al (1968) related that since only one foot at a time is on the ground, the weight acceptance is immediate upon foot strike and reaches a maximum at mid-support and gradually decreases through takeoff.

JAMES et al (1973) stated that as speed of running increased, the support phase decreased in relation to the non-support phase in time. James also stated that greater forces were exerted on the foot at foot strike caused by a forward tilting of the trunk while running. LUTHTANEN et al (1978) determined that as running speed increased from 40% to maximum, contact time and flight time decreased, but not in similiar fashions. HOSHIKAWA et al (1973) measured the swing, support, and stride phase times during speed increases. The findings indicated that all three phase times decreased with the support phase exhibiting the greatest reduction.

In analyzing runners during competition, it was determined that as speed decreased there was less effort required to handle the impact at foot contact. On this

basis it was concluded that a more vertical leg is advantageous, ADRIAN et al (1973).

In their temporal analysis of highly skilled female runners, BATES et al (1973) were unable to distinguish between the foot strike and mid-support phases. They judged the duration of foot strike to be less than 0.01 seconds. A mean of 0.1164 and 0.1182 seconds was reported for the total support time of the right and left foot respectively. The foot strike and mid-support phases accounted for approximately 40%, and the takeoff phase approximately 60% of the total support time.

ELLIOT et al (1979) stated that the anthropometric dimensions of the support limb of a jogger influenced the large forces generated at foot strike.

Based on film data of five subjects during the 400 meter run, BATES et al (1979) was able to divide the support phase of the stride into three categories: deceleration, transition, and acceleration. The mean percentages of the three sub-phases was 36.22, 31.83, and 31.95 respectively. The approximate length of time for the entire support phase was 0.12 seconds. ELLIOT et al (1976) used 4.8 m/s as the cutoff point between jogging and running and determined the group means for male and female joggers for the support phase to be 0.227 and 0.212 seconds respectively for overground jogging, and 0.233 and 0.211 seconds for treadmill jogging. In a similiar study NELSON et al (1972) reported group means of 0.254, 0.201, and 0.162 seconds for

velocities of 3.35, 4.88, and 6.4 m/s during horizontal overground running. Group means of 0.255, 0.207, and 0.175 seconds were reported for treadmill velocities of 3.35, 4.88, and 6.4 m/s respectively.

NELSON et al (1971) stated that with an increase in running velocity, stride length and stride rate increased while the period of support decreased. It was further stated that altering the running slope from a 10% downgrade, to the horizontal, and to a 10% upgrade, resulted in decreased stride length, decreased support time, and non-support time and increased stride rate.

Historically, both simple and elaborate instruments and techniques have been used for gait analysis. A black rubber mat, studded with pyramidial projections, was placed over a glass plate by ELFTMAN (1934) to study the pressure distribution in the foot of an individual walking over the mat. By further introducing a reflecting fluid into the spaces between the projections, filming the image of pressure distribution was possible.

Through the use of his electrobasograph, SCHWARTZ et al (1934) was able to determine various temporal parameters of the human gait. In the report it was stated that with increased stride rate the support phase time decreased.

HOLDEN et al (1953) built a pressure-sensitive element which was inserted between the subject's foot and

shoe. The element, a double condenser, measured the pressure on the sole of the foot during walking. An increase of 30% in the walking rate produced an equivalent increase in the pressure at the corresponding time of the step. WETZENSTEIN (1961) used a similiar arrangement to determine the static and dynamic weight-bearing of the foot in a shoe. The vertical component of the heel load was calculated through the use of a stiff spring-balance in which the deflection was registered by strain-gauges.

Thin transducers attached to the bare foot measured the pressure between the foot and the floor as described by BAUMAN et al (1963). This permitted the evaluation and subsequent treatment of anaesthetic feet. A microswitch shoe was developed by WINTER et al (1972) with the capabilties of determining heel contact, flat foot, ball of foot contact, push off phase, and toe contact.

HUTTON et al (1972) developed a system consisting of beams, strain-gauges, and load cells to measure the load distribution under the foot with various types of footwear. STOTT et al (1973) used this same apparatus and reported that the duration of the support phase was from 0.68 to 0.72 seconds. It was also noted that the load during walking on a firm flat surface was low in the midfoot, ranging from 2.5% to 15% of body weight. Further conclusions stated that heavier subjects carried a greater proportion of the load on the lateral side of the forefoot.

STOKES et al (1974) used a twelve-channel

transducer-amplifier-recorder system to measure vertical loads on areas of the foot. It was approximated that 11.5% of total support time was dedicated to the foot strike phase, 50% for mid-support phase, and 38.5% for toe off phase, with the total time being 0.61 seconds for the entire support phase. Conclusions stated that healthy persons impose about 36% of total weight on the toes during the final stages of foot contact.

A "universal harness" consisting of footswitches and electric goniometers was used by ZUNIGA et al (1974) to examine the gait of 10 males, 10 females, and 10 above-knee amputees. The 10 female subjects tended toward a shorter gait cycle.

A force platform was mounted under a specially constructed treadmill with continual assessment capabilities by ISMAIL (1968). Analysis of the force tracings revealed all subjects favored one foot over the other while walking naturally. Also, heavier subjects exerted more force. In addition it was found that age and weight effect the force magnitudes more than height.

A force tracing from a runner with an estimated velocity of 8 m/s, PAYNE et al (1968), exhibited a maximum vertical force of approximately 2670 Newtons. It was also reported that a forward horizontal thrust during the early period of foot contact was followed by a backward thrust.

CAVAGNA (1975) calculated the vertical force of walking and running through the use of the equation:

$$Fv = P + ma$$

where Fv = the vertical force, P = body weight, m = mass, and a = vertical acceleration of the center of gravity of the body. Cavagna's research report included a description of eight force plates used for that work.

A sample ground reaction force record of a male jogger obtained by MILLER (1978) showed a minor peak followed by a major peak. The initial peak of approximately 1500 Newtons was attributed to impact force. This peak was followed by a larger peak, of approximately 1850 Newtons. In this case 1850 Newtons was roughly twice the body weight of the subject. In Miller's study the total contact time for the subject was 0.24 seconds.

An increase in force amplitudes, with a decrease in time of force application, was determined through force plate analysis of normal walking, race walking, and running by PAYNE (1978). The maximum vertical force of the respective techniques was approximately 800, 1600, and 3200 Newtons.

FUKUNAGA et al (1978) presented the results of a study using a force platform and a 16-mm cine camera. Careful inspection of the available graphs revealed that the contact time decreased as running velocity increased. However, the highest maximum vertical force was reported at the middle velocity with the higher and lower velocities having approximately equal, but lower maximum vertical forces.

In a comparison of sprinting and jogging patterns, YONEDA et al (1979) noted that joggers' initial contact was with the heel while sprinters' initial contact was with the ball of the foot. A comparison of the average support times for the two skills revealed 250ms for jogging and 140ms for sprinting. It was further reported that both techniques had a two peak vertical force time curve, however, the initial peak in jogging was usually less than the second with the reverse true in sprinting. The maximum force in jogging averaged 1205.4 Newtons in comparison to 1687.4 Newtons in sprinting.

This chapter has dealt with the reporting of literature dealing with temporal, spatial, kinetics, and force measurements using instrumentations specific to human gait analysis.

CHAPTER III

METHODS AND PROCEDURES

This study was designed to incorporate direct and indirect measurement techniques in an effort to validate the indirect method with direct measurement as criterion. Cinematographical procedures were developed in an attempt to reproduce the direct vertical force measurements obtained by a force platform in jogging. The University of Alberta biomechanics laboratory was the site of the simultaneous retrieval of cinematographic and force platform data. The subjects jogged across a force plate while being filmed. The two data sources were synchronized for subsequent analysis.

Subjects

For the purpose of this study twelve trials were performed by six subjects. The four males ranged in age from 27 to 62 years while the two females were 23 and 30 years old. In the second part of this study three subjects were used. These subjects were chosen at random. Subject EU-1 was a 23 year old female with a total body weight of 517.4N. Subject JT-2, a 44 year old male, had a body

weight of 859.5N and subject GS-3 weighed 637N and was a 62 year old male. In total body weight, the males ranged from 637.0 to 997.6 Newtons while the females weighed 517.4 and 570.4 Newtons. The subjects were instructed to first jog bare foot and then wearing standard jogging shoes. On a total of twelve runs with six in each category, the subjects jogged along a raised jogging platform and contacted a force plate embedded in the platform. Each subject was given as many trials as needed to contact the force plate without altering the stride or looking at the force measuring device. The subject decided which foot to use for contacting the force plate.

Apparatus

Two Photo Sonics 1PL 16mm pin registered cameras were used for data acquisition. Both cameras were fitted with an Angenieux 12-120 zoom lens. A phase lock system was used to ensure synchronized data between the two cameras.

Camera one, which recorded the side view of the subjects, was positioned with its optical axis bisecting the force platform and perpendicular to the joggers' plane of motion. The camera was leveled, 12 meters from the platform, at a height of 1.2 meters.

Camera two recorded the force platform output display from a Tektronix 465 oscilloscope. This camera was

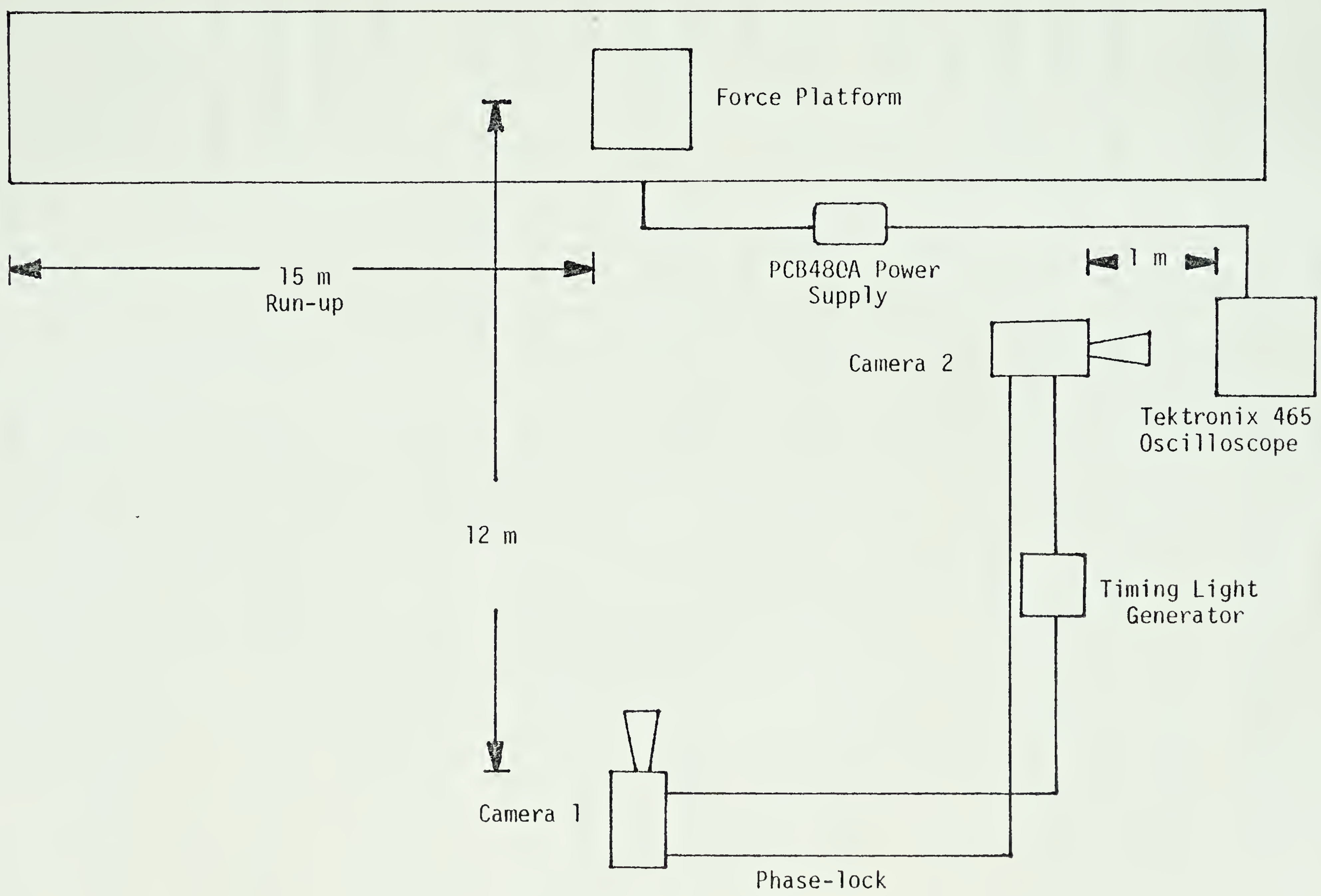


FIGURE 1

EXPERIMENTAL SETUP

positioned 1.0 meter from the oscilloscope and adjusted so the entire screen from the oscilloscope encompassed the field of view of the camera.

For both cameras a frame rate of 100 FPS and a shutter angle of 30° resulted in an exposure time of 1/1200 second. Ektachrome 7250 color film with an ASA rating of 400 was used. The film was force processed one stop to produce an equivalent rating of 800 ASA. A Pentax 1° Spotmeter VI was used for all light measurements.

A timing light generator, which produced light marks on the edge of the films, was connected to both cameras. The timing light generator was set at a flash frequency of 10 Hz and switched to 100 Hz for roughly 0.1 seconds after the cameras reached operating speed. The marks produced on the film were used to determine the actual camera frame rate and also served as reference points for matching of frames on the two films.

A Stoelting's Force Sensitive Platform was modified for use in this study. The modification involved the removal of the "Linear Variable Differential Transformers" and installation of a PCB208A04 piezoelectric force transducer for measuring the vertical force component. A support device was designed and machined to permit the modification. The transducer was powered by a PCB480A DC power supply. A Tektronix 465 oscilloscope was used to output the analog force signal from the transducer. The oscilloscope was operating with a sensitivity of 0.01

volts/division.

The force platform was fitted into a specially constructed casing and leveled with a 22.0cm raised jogging platform. This ensured a completely flush jogging surface. A 1.0 meter area on the force platform in the plane of motion was marked for later computation of projected size to real life size.

Calibration

The transducer used for vertical force measurement was calibrated by the manufacturer and reported to be linear to within 1% and to have a maximum compression of 4450N. The linearity was tested from 0.0 to 1200N in 225N intervals and found to be consistent with the manufacturer's claims.

The modified force platform was checked for uniformity of measurements. The area of homogeneity was carefully marked and any trial by a subject with the foot contacting outside the specified area was discarded.

Testing Procedures

The subjects were given as many practices as necessary to enable them to contact the "live" area on the force plate consistently without altering their stride or looking at the plate. Once subjects felt ready, they stood on the platform to obtain a record of their vertical body

mass force displacement on the oscilloscope. The subjects' jogging trials were then recorded. The area of foot contact with the force plate was checked for proper contact within the "live" area.

Data Analysis

The two synchronized films were initially edited and matched according to the timing marks on the edges of the films. Film one, from camera one, contained a record of the jogging activity while film two, from camera two, contained the force plate data from the oscilloscope.

A Triad VR/100 pin registered film analyzer was used to project the image onto a Bendix Digitizing Board (accuracy ±0.001 inch). Both the analyzer and digitizing board were leveled in all directions and aligned so the optical axis of the analyzer was perpendicular to the digitizing board.

A Bendix Cursor was utilized, via a Hewlett Packard 9864A digitizer, to enter a standard reference point and all subsequent coordinate points into a Hewlett Packard 9825B desk top computer. All data was stored on magnetic computer tapes.

Initially, every frame of the subject film was digitized for calculation of the maximum height attained by the center of mass of the body during the flight phase and the height of the center of mass at the instant of foot

contact with the force platform. The digitizing required the input of the proximal and distal X/Y coordinates of the following body segments: 1)head and neck, 2)trunk, 3)upper arm, 4)lower arm, 5)hand, 6)upper leg, 7)lower leg, and 8)foot. The subsequent computations of vertical force calculations from biomechanics cinematography required data from every fourth frame of the subject film.

The force plate data film was digitized on all frames. The analysis required the input of the Y coordinate of the ensuing items: 1)oscilloscope reading with force plate under no load, 2)displacement on the oscilloscope resulting from subject's body weight, and 3)displacement on the oscilloscope due to force changes during jogging.

The Humanscale Anatomical Data (DIFFRIENT 1979) was used for all body segment parameters required within the scope of this study.(Figure 2)

Computations

The computation of the vertical force component through cinematographical procedures was achieved as follows.

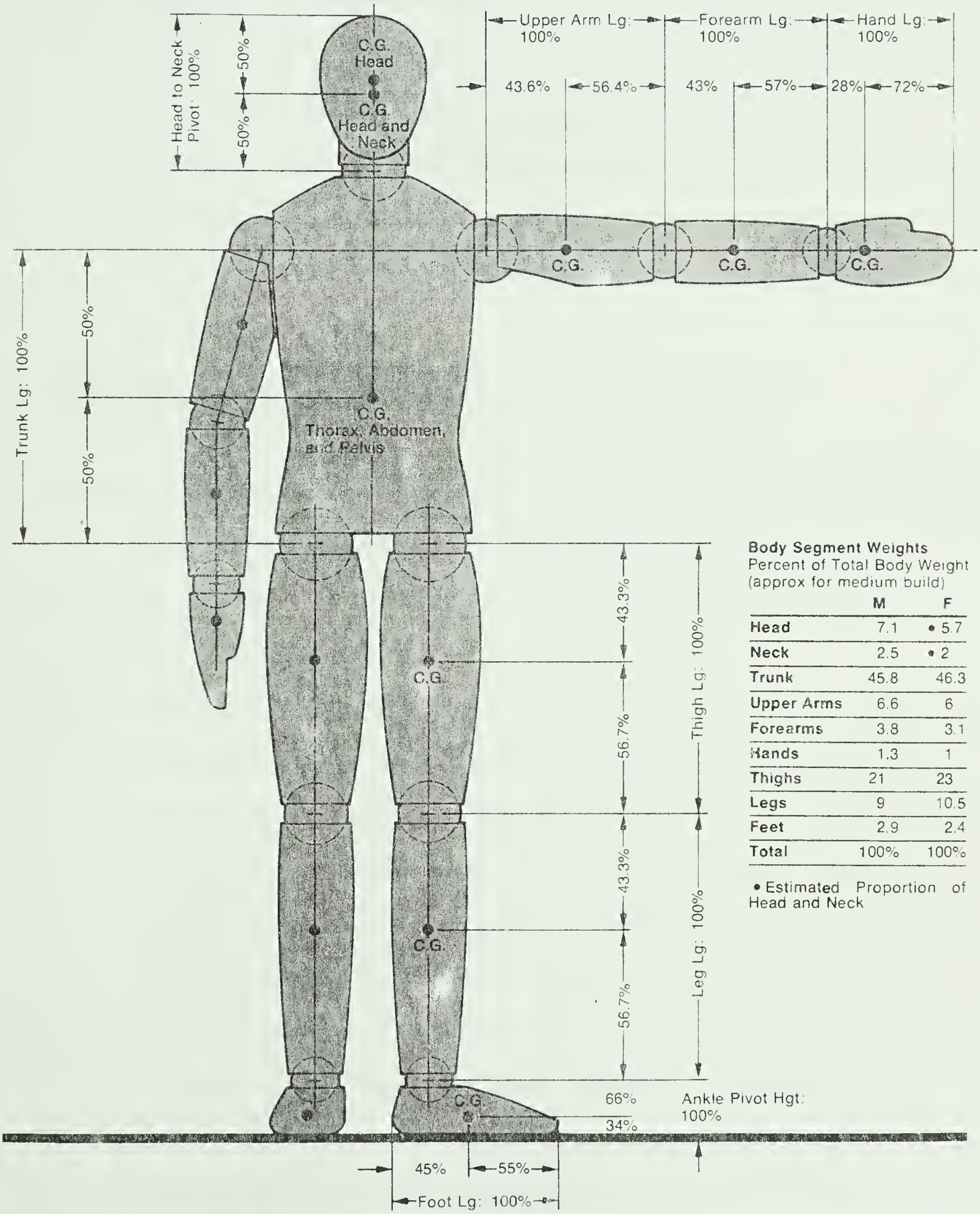
Temporal Measurements

The first part of this study, using 12 trials, was conducted to determine various temporal measurements of the support phase in jogging. The total time of the entire support

FIGURE 2

HUMANSCALE ANATOMICAL DATA

(DIFFRIENT 1979)



Body Segment Weights
Percent of Total Body Weight
(approx for medium build)

	M	F
Head	7.1	• 5.7
Neck	2.5	• 2
Trunk	45.8	46.3
Upper Arms	6.6	6
Forearms	3.8	3.1
Hands	1.3	1
Thighs	21	23
Legs	9	10.5
Feet	2.9	2.4
Total	100%	100%

• Estimated Proportion of Head and Neck

phase as well as the times for the foot strike, mid-support, and takeoff phases of the support phase were determined both in absolute terms and percentages. This preliminary investigation was designed to provide the researcher with all pertinent temporal data. The various temporal measurements were determined from the cinematographical records of the force platform output display on the oscilloscope, and in the case of the differentiation between the mid-support and takeoff phases, both synchronized films were used to locate the instant the heel began to rise off the running surface.

Vertical Force Calculations using Biomechanics Cinematography

Three subjects were chosen at random from the six subjects for subsequent analysis of the vertical force parameters in jogging. The calculation of the vertical force compontent was achieved through three steps.(Figure 3)

1. Foot strike phase (To determine the force of impact)
   The equation of uniformly accelerated motion due to gravity was used to determine the velocity with which the subject was descending from the flight phase in jogging when foot contact ocurred. The maximum height reached by the center of mass of the body during the flight period was determined. The height of the center of mass of the body at the instant of foot contact was also computed. The difference between the two heights represented the actual distance the body fell. By use

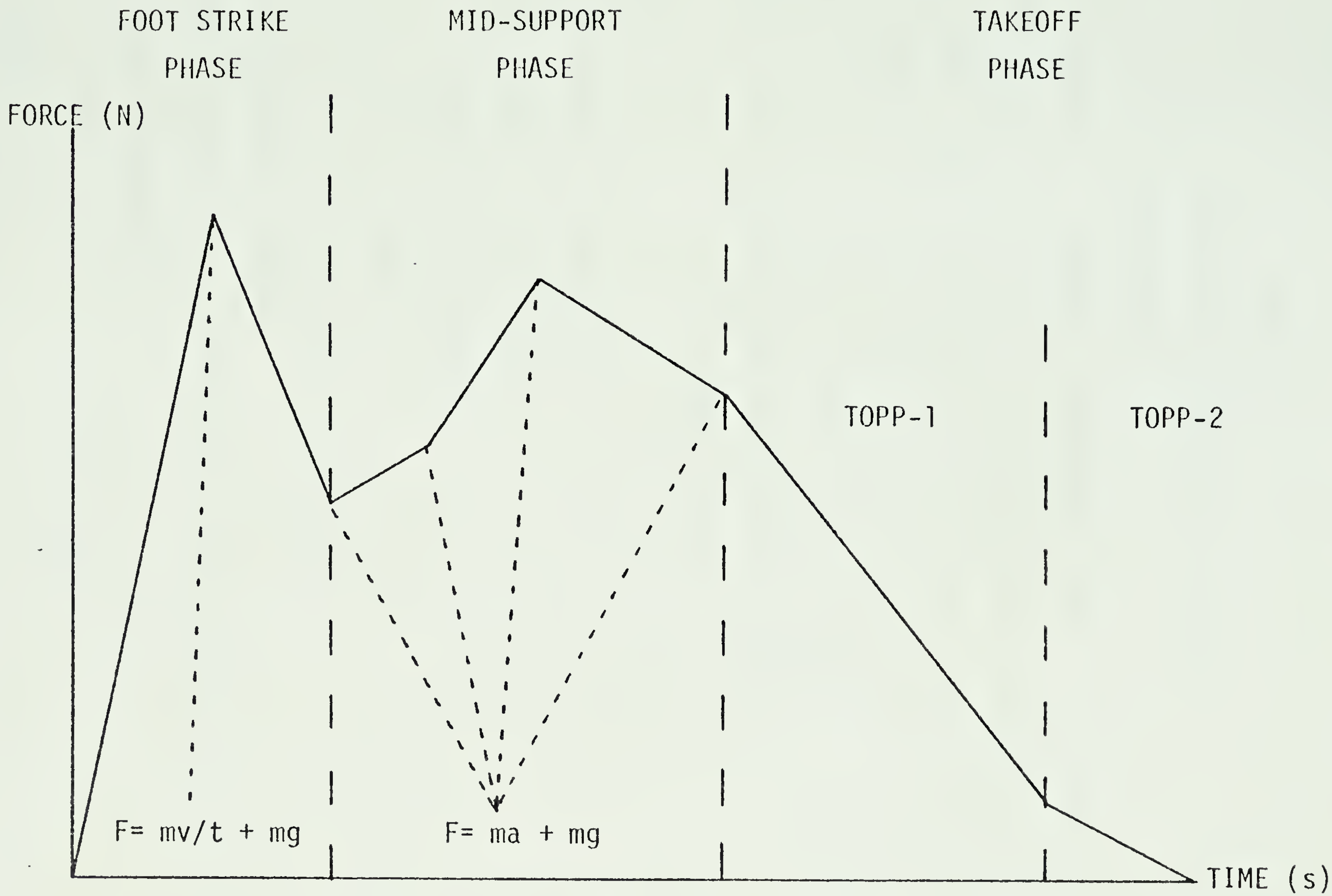


FIGURE 3

SCHEMATIC DIAGRAM OF CINEMATOGRAPHICAL CALCULATIONS

of the equation

$$V = \sqrt{2gd}$$

where

V= final velocity

g= acceleration due to gravity

d= displacement

the velocity at impact was determined. The length of time of the foot strike phase, in relation to the total contact time with the force plate, was derived from calculating the mean percent for all subjects as determined in the temporal phase of this study. The force of impact, (foot strike phase), was then calculated by the equation

$$F = mv/t + mg$$

where

F= force of impact

m= mass of the body

v= velocity at impact

t= time of impact

g= acceleration due to gravity

2. Mid-support phase

The forces along the force time curve during this phase were computed by

$$F = ma + mg$$

where

F= vertical force component

m= mass

a= vertical acceleration of the center of mass of

the body

g= acceleration due to gravity

3. Takeoff phase

In order to minimize the error within the cinematographical analysis of the takeoff phase of the jogging stride, a technique was devised which divided the takeoff phase into two separate sections, takeoff phase part-1 (TOPP-1) and takeoff phase part-2 (TOPP-2). TOPP-1 is that portion of the takeoff phase which begins the instant the heel rises off the running surface; the end of of the mid-support phase. TOPP-1 terminates when an assigned percentage of time remains in the entire support phase. TOPP-2 originates at the termination of TOPP-1 and continues until the toes break contact with the running surface (i.e. the end of the entire support phase). The point of differentiation between TOPP-1 and TOPP-2 is that point at which the angle between the force-time curve and the tangent at that point is the largest, visually, when the force-time curve begins to tail off as the force values approach zero. The elapsed time for the TOPP-2 portion was determined in the preliminary temporal study by computing the mean percent time of the TOPP-2 portion of all subjects. The initial force value for the TOPP-2 portion was determined by calculating the mean, of all subjects, percent body weight which occurred as the initial TOPP-2 reading from the force platform data.

The entire takeoff phase was then graphically represented by one straight line from the final point in the mid-support phase to the initial point of the TOPP-2 portion and a second straight line from the initial TOPP-2 point to the point when the toes break contact with the running surface and the vertical force reached zero.

Summary

The preceeding chapter has dealt with the methods and procedures involved within this study. In particular, a description of the equipment, calibration and its operation was elaborated. The procedures involved in the actual retrieval of data and analysis were described and an explanation of the computational procedures for determining the vertical force from cinematography was made.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

The results obtained from this study are categorized and presented under four headings.

1. Preliminary temporal measurements:
   Calculations of the mean percent of the foot strike and TOPP-2 portion of the takeoff phase to the entire support phase.
2. Direct force measurements:
   Results obtained from the force platform including force-time graphs and tables.
3. Cinematography measurements:
   Results obtained from biomechanics cinematography analysis.
4. Comparative analysis:
   Comparison of the two techniques of measurement, including graphs and tables of differences within the various phases of the support phase of jogging.

Preliminary Temporal Measurements

In calculating the percentage of time the foot strike phase occupied as part of the entire support phase, 12 trials were used and the total support time and total time for the foot strike phase for all 12 trials was determined from the film. The total elapsed time of the support phase ranged from a low of 0.18 seconds to a high of 0.23 seconds with a mean of .21 seconds. The time of the foot strike phase (i.e. the time over which the impact transpired), varied between 0.03 to 0.05 seconds and displayed an average time of 0.04 seconds. By calculating the percentages of the foot strike phase to the entire support phase, a mean of 21% was found. The 21% represents the average proportional value of the entire support phase occurring as the foot strike phase.(Table 1)

A similiar calculation to determine the percentage of the support phase made up by the TOPP-2 portion of the takeoff phase also used the 12 trials. The data retrieved from the force platform revealed a range from 0.02 to 0.04 seconds with a mean of 0.03 seconds for the total length of time of the TOPP-2 portion. Upon completion of the percentage computations, a range from 10% to 19% resulted in a mean of 14% of the total support time taken up by the TOPP-2 portion of the takeoff phase. This 14% gave the x-value (time) for all subjects.(Table 2)

By computing the proportion of total body weight

TABLE 1

DETERMINATION OF TEMPORAL IMPACT DATA

Trial#	TSPT[1]	IMPT[2]	PCT[3]
1	0.21	0.04	19%
2	0.19	0.03	16%
3	0.21	0.05	24%
4	0.21	0.03	14%
5	0.23	0.05	22%
6	0.20	0.04	20%
7	0.23	0.05	22%
8	0.23	0.04	17%
9	0.20	0.05	25%
10	0.21	0.05	24%
11	0.21	0.04	19%
12	0.18	0.05	28%
			Mean= 21%

[1] Total time for the entire support phase in seconds

[2] Total time for the foot strike phase in seconds

[3] Percentage of foot strike to entire support phase

TABLE 2

DETERMINATION OF TOPP-2 INITIAL TEMPORAL DATA POINT

Trial#	TSPT[1]	FPTT[2]	PCT[3]
1	0.21	0.03	14%
2	0.19	0.03	16%
3	0.21	0.04	19%
4	0.21	0.02	10%
5	0.23	0.03	14%
6	0.20	0.02	10%
7	0.23	0.04	17%
8	0.23	0.03	13%
9	0.20	0.03	15%
10	0.21	0.03	14%
11	0.21	0.03	14%
12	0.18	0.03	17%
			Mean= 14%

[1] Total time for the entire support phase in seconds
[2] Total time for TOPP-2 portion in seconds from force platform data
[3] Percentage of TOPP-2 to entire support phase

which occurred as the force reading at the initial point of the TOPP-2 portion for all subjects, it was found that approximately 1/3 or 33% of the total body weight was expressed as the initial force reading. Subsequently, the y-value (force) was obtained by taking 33% of the subject's weight.

Direct Force Measurements

The results obtained from the force platform ascribe to a curve with an initial peak of short time duration followed by a second peak with a gradual descent to a force value of zero.(Tables 3,4,5)(Figures 4,5,6) The initial peak, the foot strike phase, reached its maximum in 0.02 seconds after foot contact with the force platform. The maximum value of the foot strike phase for all subjects was between 3.3 and 4.0 times the body weight of the subject.

The mid-support phase, which began when the force-time curve reached its lowest point immediately following the foot strike phase, was found to begin within 0.04 to 0.05 seconds after the initial foot contact occurred for all subjects. The mid-support phase terminated for two of the subjects in 0.05 seconds and in 0.07 seconds for the third subject. The maximum force exhibited during the mid-support phase was 1022.3N for subject EU-1, 3085.2N for subject JT-2, and 1958.3N for subject GS-3. In the case of

TABLE 3

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT EU-1

Time*	Force**	Time	Force
0.00	0.0	0.12[c]	952.2
0.01[a]	384.6	0.13	923.1
0.02	1853.1	0.14	812.0
0.03	858.2	0.15	694.0
0.04	683.8	0.16	570.9
0.05[b]	630.8	0.17	451.3
0.06	864.9	0.18	323.1
0.07	1020.6	0.19[d]	223.9
0.08	1013.7	0.20	133.3
0.09	1022.3	0.21	44.5
0.10	1000.0	0.22	0.0
0.11	991.5		

* Measured in seconds

** Measured in Newtons

[a] Initial point of contact

[b] Start of mid-support phase

[c] Start of takeoff phase (TOPP-1)

[d] Start of takeoff phase (TOPP-2)

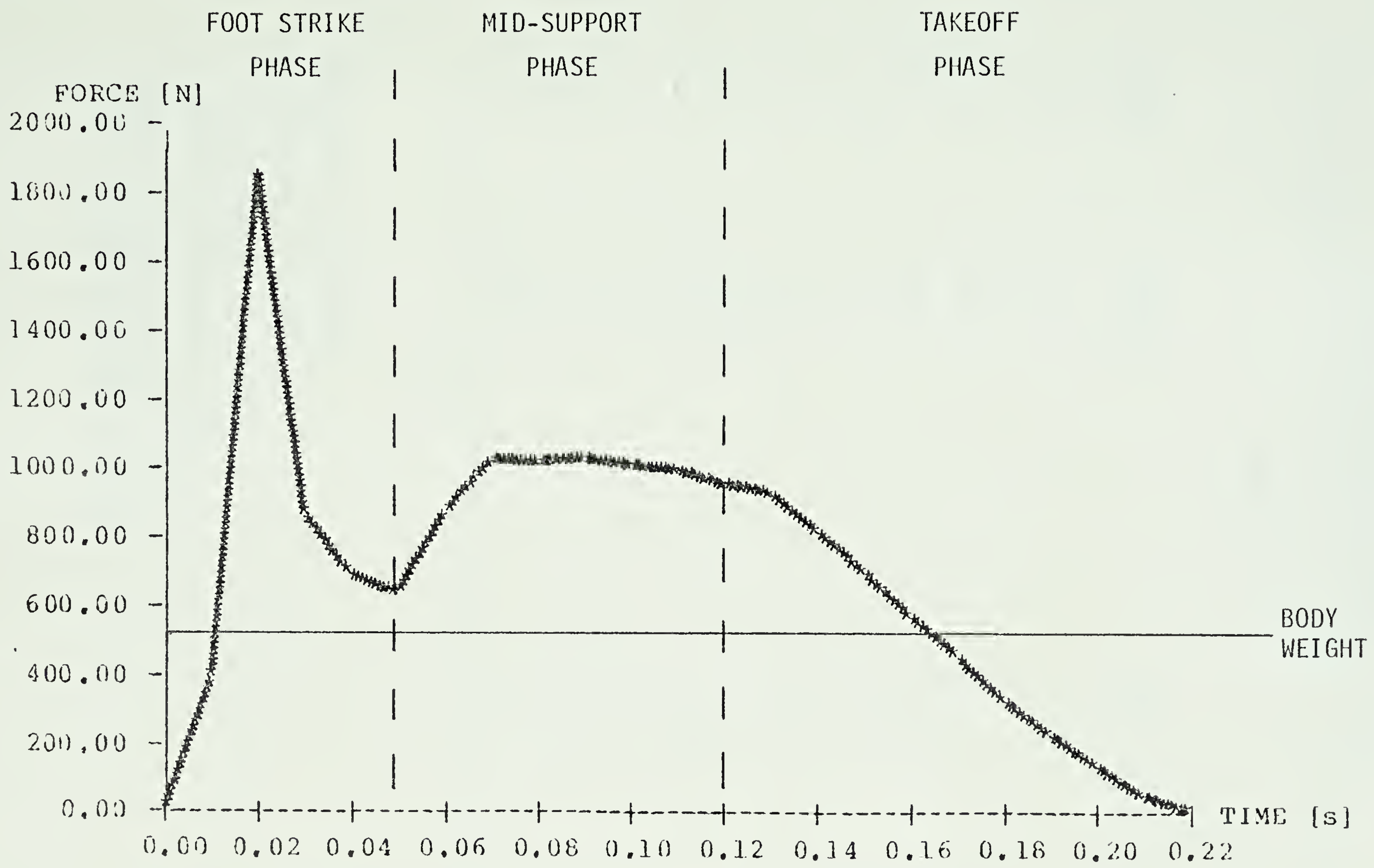


FIGURE 4

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT EU-1

TABLE 4

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT JT-2

Time*	Force**	Time	Force
0.00	0.0	0.11	2084.9
0.01[a]	1455.6	0.12	1852.4
0.02	2833.1	0.13	1614.9
0.03	2496.4	0.14	1388.9
0.04[b]	2021.6	0.15	1149.8
0.05	2624.9	0.16	853.8
0.06	3085.2	0.17	552.9
0.07	2956.7	0.18[d]	269.9
0.08	2956.7	0.19	112.2
0.09[c]	2732.3	0.20	74.8
0.10	2390.7	0.21	0.0

* Measured in seconds

** Measured in Newtons

[a] Initial point of contact

[b] Start of mid-support phase

[c] Start of takeoff phase (TOPP-1)

[d] Start of takeoff phase (TOPP-2)

FIGURE 5

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT JT-2

TABLE 5

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT GS-3

Time*	Force**	Time	Force
0.00	0.0	0.11	1432.5
0.01[a]	565.1	0.12	1264.7
0.02	2571.8	0.13	1121.2
0.03	1822.3	0.14	911.1
0.04[b]	1525.7	0.15	714.7
0.05	1689.3	0.16	527.4
0.06	1958.3	0.17	311.3
0.07	1935.6	0.18[d]	160.2
0.08	1931.1	0.19	99.7
0.09[c]	1766.4	0.20	27.2
0.10	1675.7	0.21	0.0

* Measured in seconds

** Measured in Newtons

[a] Initial point of contact

[b] Start of mid-support phase

[c] Start of takeoff phase (TOPP-1)

[d] Start of takeoff phase (TOPP-2)

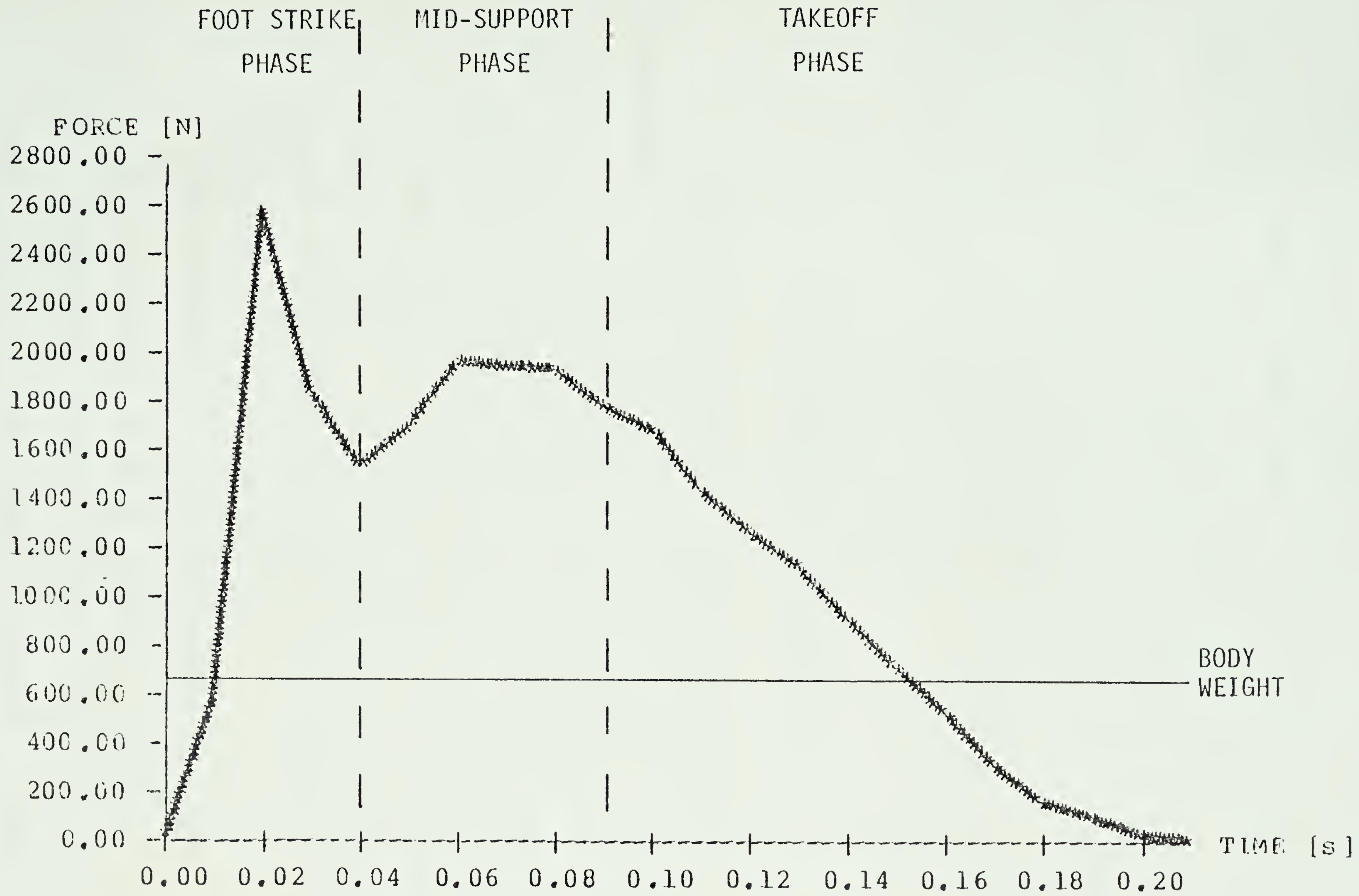


FIGURE 6

VERTICAL FORCE FROM FORCE PLATFORM

SUBJECT GS-3

subject JT-2, the maximum force of 3085.2N found in the mid-support phase was larger than the force of impact in the foot strike phase. For subject EU-1 and GS-3 the force of impact during the foot strike phase was larger.

The takeoff phase was graphically depicted as a gradually descending force-time curve exhibiting a tailing off effect as the force values approached zero. The total time for the takeoff phase was 0.09 seconds for subject EU-1 and 0.12 seconds for both subjects JT-2 and GS-3.

Cinematography Measurements

The calculations of the vertical force measurements from biomechanics cinematography resulted in an initial peak, the duration of which was assigned 21% of the total time of the support phase, followed by a second peak which descended gradually and ultimately led to the final portion which tailed off toward force values of zero. The final portion, TOPP-2, of the cinematography measurements was assigned 14% of the total time of the support phase.(Tables 6,7,8) (Figures 7,8,9)

The calculation of the maximum value for the foot strike phase (i.e. the force of impact), resulted in values of 1885.4, 3010.2 and 2664.4N for subjects EU-1, JT-2, and GS-3 respectively. These values represent a range from 3.5 to 4.1 times the body weight of the subject.

The mid-support phase, which for subject EU-1

TABLE 6

VERTICAL FORCE FROM CINEMATOGRAPHY

SUBJECT EU-1

	Time*	Force**
Foot Strike Phase		
	0.00	0.0
	0.022	1885.4[a]
	0.044	831.5
Mid-Support Phase		
	0.06	728.7
	0.09	1256.7
	0.12	1010.2
Takeoff Phase		
TOPP-1		
	0.15	651.5
	0.18	292.1
TOPP-2		
	0.19	172.5[b]
	0.22	0.0

* Measured in seconds

** Measured in Newtons

[a] Calculated force of impact

[b] 1/3 body weight at 14% from end of support phase

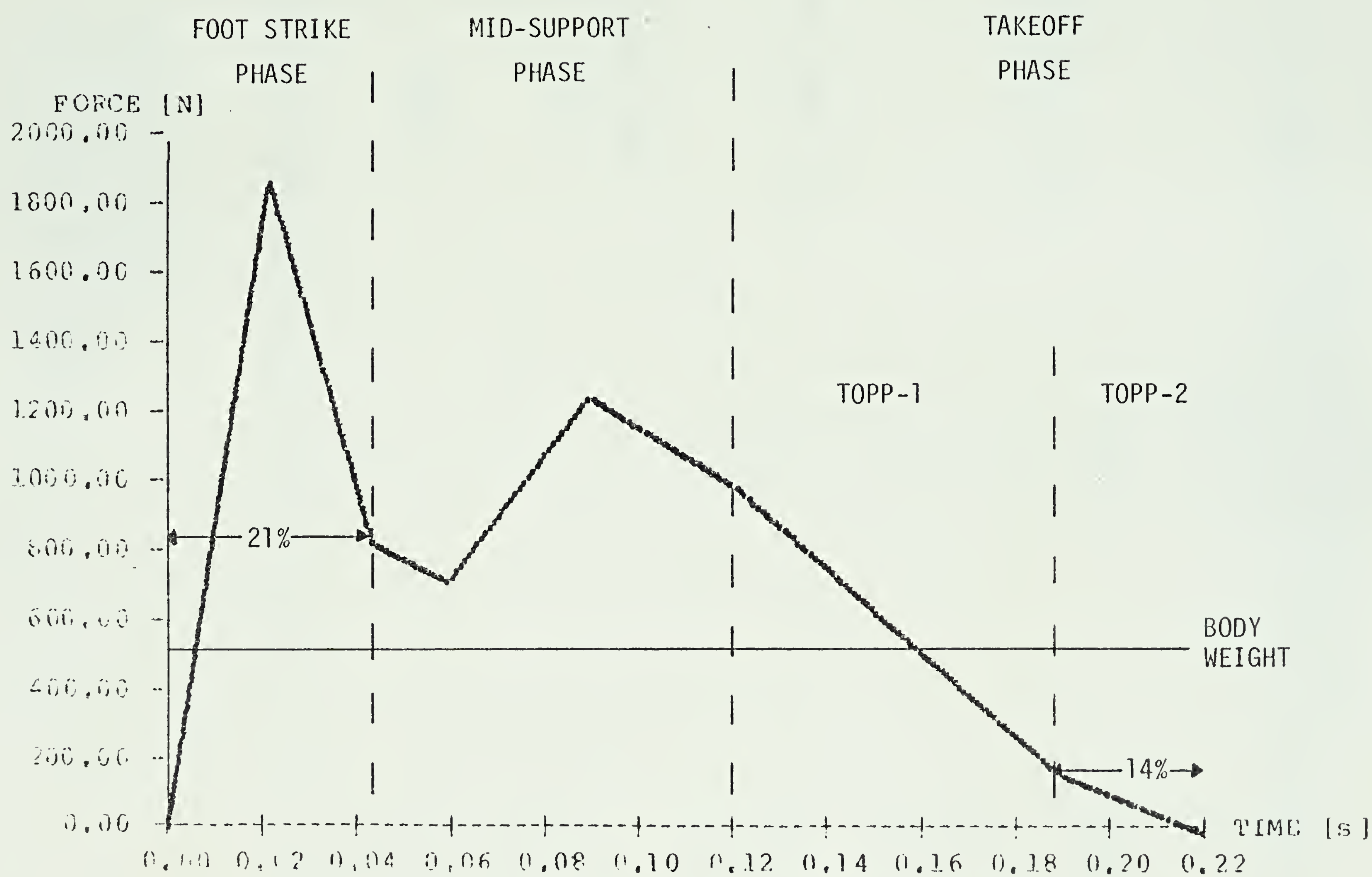


FIGURE 7
VERTICAL FORCE FROM CINEMATOGRAPHY
SUBJECT EU-1

TABLE 7

VERTICAL FORCE FROM CINEMATOGRAPHY

SUBJECT JT-2

	Time*	Force**
Foot Strike Phase		
	0.00	0.0
	0.021	3010.2[a]
	0.042	1659.8
Mid-Support Phase		
	0.06	1853.4
	0.09	2788.9
Takeoff Phase		
TOPP-1		
	0.12	1954.8
	0.15	1120.6
TOPP-2		
	0.18	286.5[b]
	0.21	0.0

* Measured in seconds

** Measured in Newtons

[a] Calculated force of impact

[b] 1/3 body weight at 14% from end of support phase

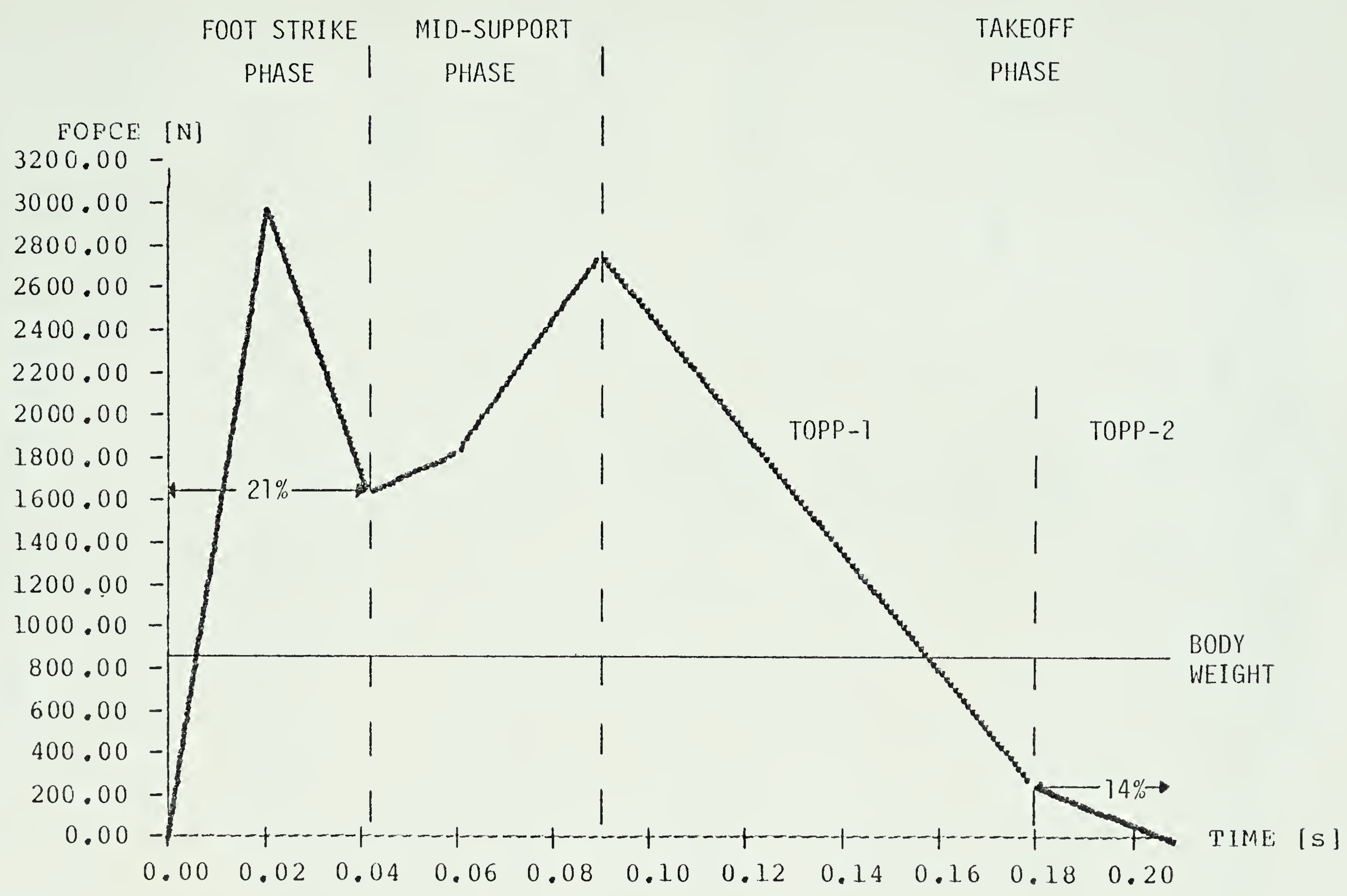


FIGURE 8

VERTICAL FORCE FROM CINEMATOGRAPHY

SUBJECT JT-2

TABLE 8

VERTICAL FORCE FROM CINEMATOGRAPHY

SUBJECT GS-3

	Time*	Force**
Foot Strike Phase		
	0.00	0.0
	0.021	2664.4[a]
	0.042	1058.0
Mid-Support Phase		
	0.06	2305.3
	0.09	2002.0
Takeoff Phase		
TOPP-1		
	0.12	1405.4
	0.15	808.9
TOPP-2		
	0.18	212.3[b]
	0.21	0.0

* Measured in seconds

** Measured in Newtons

[a] Calculated force of impact

[b] 1/3 body weight at 14% from end of support phase

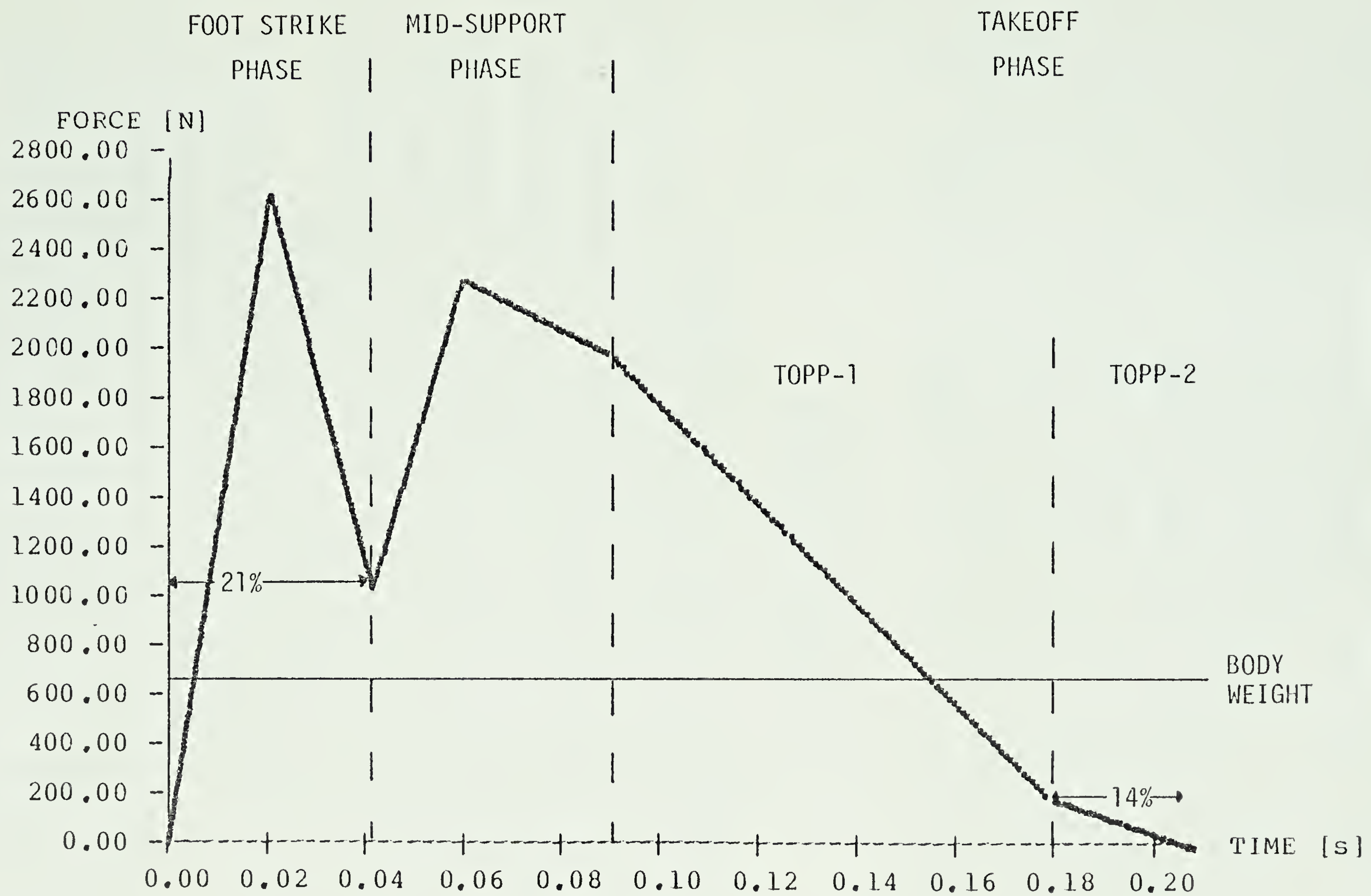


FIGURE 9

VERTICAL FORCE FROM CINEMATOGRAPHY

SUBJECT GS-3

spanned 0.06 seconds and 0.03 seconds for subjects JT-2 and GS-3, in all cases had a maximum value less than the maximum force during the foot strike phase.

The TOPP-2 portion of the takeoff phase began when 14% of the total support phase time remained. For all subjects 14% was 0.03 seconds of the support phase. In all cases the initial force value for the TOPP-2 portion was assigned 33% of the total body weight; 172.5N for subject EU-1, 286.5N for subject JT-2, and 212.3N for subject GS-3.

Comparative Analysis

In comparing the results, as obtained from the direct force measurements and biomechanics cinematography, the measurements from the individual phases within the support phase were compared initially and then the measurements from the entire support phase were compared. Both graphic and tabular forms were used to depict the comparative analyses.(Tables 9,10,11)(Figures 10,11,12)

Within the foot strike phase a mean difference of +100.7N was found between the force plate and biomechanics cinematography data for the three subjects. The cinematography calculation for all subjects produced higher forces than the force plate data, from 32.3N to 177.1N, with maximum force computations ranging from 1885.4N to 3010.2N.

The cinematography data of the mid-support phase exhibited a mean value of 62.5N below the force platform

TABLE 9

COMPARISON OF CINEMATOGRAPHY AND FORCE PLATFORM DATA

SUBJECT EU-1

	Time[1]	FP[2]	BC[3]	D[4]
Foot Strike Phase				
	0.022	1853.1	1885.4	+32.3
Mid-Support Phase				
	0.06	864.9	728.7	-136.2
	0.09	1022.3	1256.7	+234.4
	0.12	952.2	1010.2	+58.0
Takeoff Phase				
TOPP-1				
	0.15	694.0	651.1	-42.9
	0.18	323.1	292.1	-31.0
TOPP-2				
	0.19	223.9	172.5	-51.4

[1] Measured in seconds

[2] Force platform data in Newtons

[3] Biomechanics cinematography data in Newtons

[4] Difference between measurements from biomechanics cinematography and force platform data in Newtons

FIGURE 10

COMPARISON: CINEMATOGRAPHY(-) vs FORCE PLATFORM(*)

SUBJECT EU-1

TABLE 10

COMPARISON OF CINEMATOGRAPHY AND FORCE PLATFORM DATA

SUBJECT JT-2

	Time[1]	FP[2]	BC[3]	D[4]
Foot Strike Phase				
	0.021	2833.1	3010.2	+177.1
Mid-Support Phase				
	0.06	3085.2	1853.4	-1231.8
	0.09	2732.3	2788.9	+56.6
Takeoff Phase				
TOPP-1	0.12	1852.4	1954.8	+102.4
	0.15	1149.8	1120.6	-29.2
TOPP-2	0.18	269.9	286.5	+16.6

[1] Measured in seconds

[2] Force platform data in Newtons

[3] Biomechanics cinematography data in Newtons

[4] Difference between measurements from biomechanics cinematography and force platform data in Newtons

FIGURE 11

COMPARISON: CINEMATOGRAPHY(-) vs FORCE PLATFORM(*)

SUBJECT JT-2

TABLE 11

COMPARISON OF CINEMATOGRAPHY AND FORCE PLATFORM DATA

SUBJECT GS-3

	Time[1]	FP[2]	BC[3]	D[4]
Foot Strike Phase				
	0.021	2571.8	2664.4	+92.6
Mid-Support Phase				
	0.06	1958.3	2305.3	+347.0
	0.09	1766.4	2002.0	+235.6
Takeoff Phase				
TOPP-1				
	0.12	1264.7	1405.4	+140.7
	0.15	714.7	808.9	+94.2
TOPP-2				
	0.18	160.2	212.3	+52.1

[1] Measured in seconds

[2] Force platform data in Newtons

[3] Biomechanics cinematography data in Newtons

[4] Difference between measurements from biomechanics cinematography and force platform data in Newtons

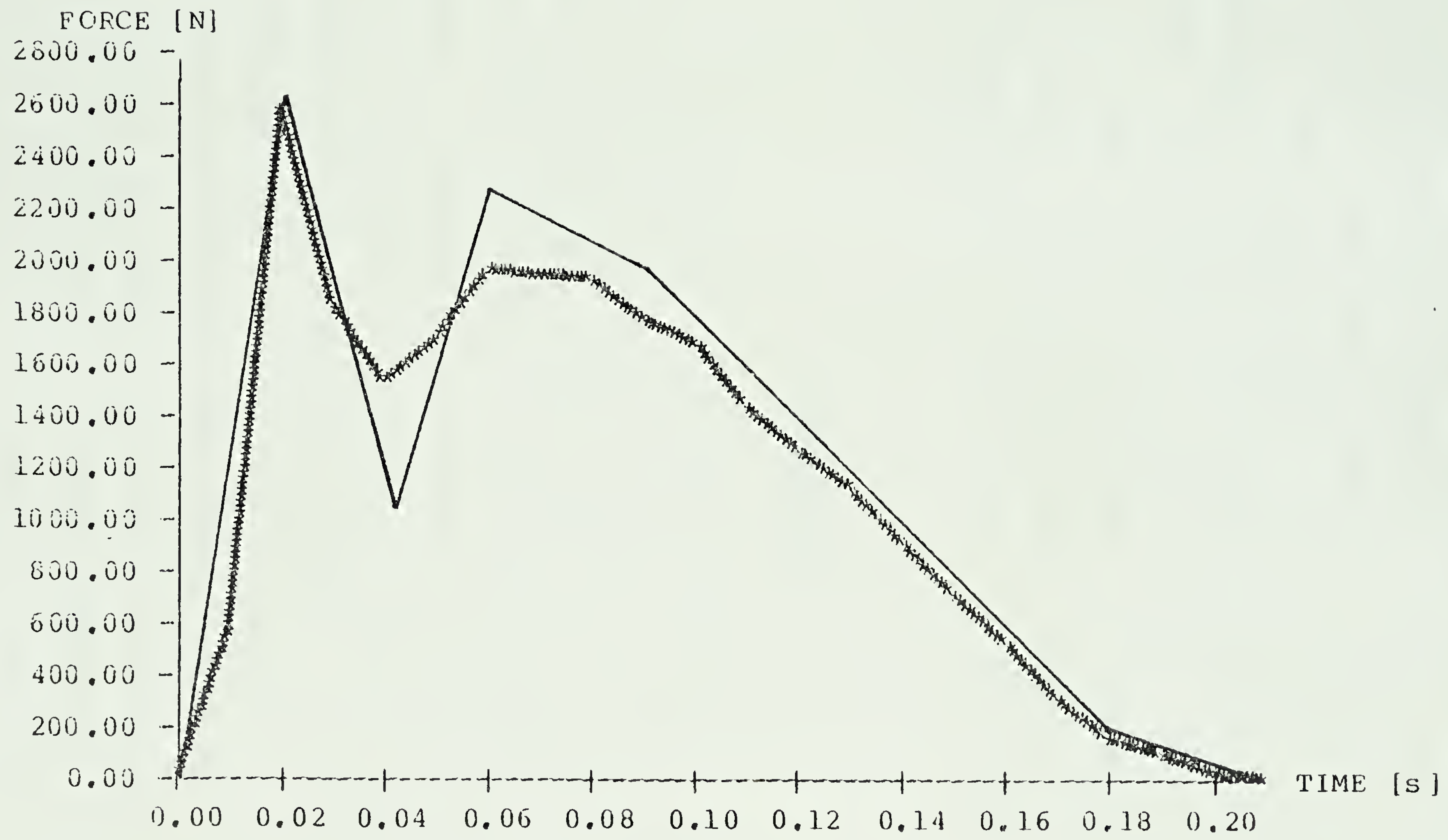


FIGURE 12

COMPARISON: CINEMATOGRAPHY(-) vs FORCE PLATFORM(*)

SUBJECT GS-3

data. Subject JT-2 had force values, for the most part, below the force plate values while subjects EU-1 and GS-3 yielded force values mainly above the criterion.

The takeoff phase, TOPP-1 and TOPP-2 inclusive, ranged from -51.4N to 140.7N above the force platform results. This produced a mean difference of +27.9N.

When the entire procedure of biomechanics cinematography was taken into account compared to direct force measurements, a total error of 6.2N was found over the three subjects.

Discussion

Within the limitations of this study, the obtained results indicate a favorable response to the question of whether biomechanics cinematography is of a practical value in the determination of vertical force characteristics in jogging. Cinematography eliminates the need for any physical limitations or laboratory controlled experimental procedures for the acquisition of data. Through the use of biomechanics cinematography procedures, data is easily obtainable and if so desired, without the subject's knowledge. This guarantees a true life performance as compared to one in which alternate experimental procedures could very easily cause the subject's performance to be unnatural.

The discussion of the results obtained in this

study has been divided into several sections.

1. <u>Preliminary temporal measurements:</u>

The determination of the total time for the support phase in jogging, a mean value of 0.21 seconds, is in strong agreement with a temporal study by ELLIOT et al (1976) in which group means for the total support phase time were reported to be 0.227 and 0.212 seconds for male and female joggers. In two other studies reporting support phase times, a sample ground reaction force record of a male jogger by MILLER (1978) displayed a total contact time of 0.24 seconds and YONEDA et al (1979) reported the support time for average joggers at 0.25 seconds. The calculated time of 0.21 seconds is an accurate mean when considering previous studies and the reports published.

The computation of 21% for the time span of the foot strike phase proved to be accurate. When the force of impact was graphically displayed as occurring over 21% of the total support phase time, the initial peak was almost identical to the force platform data. Similiarly, the calculation of 14% of the support phase dedicated to the TOPP-2 portion was also close to the force platform data. Without the addition of the TOPP-1 and TOPP-2 portions, the error within the takeoff phase would have been greater had it been represented by one straight line or by calculating the takeoff phase in the same manner as the mid-support phase.

2. Foot strike phase:

When calculating values as large as those found within the foot strike phase in jogging, a mean error of 100.7N is small. For example, in the calculation of a vertical force of impact of 3000N an error of 100N represents an error of only 3.33%. For this reason, the use of the equation for calculating impact forces during the foot strike phase seems satisfactory.

3. Mid-support phase:

The calculation of the vertical forces during the mid-support phase was completed in the same manner as a study on walking and running by CAVAGNA (1975). The overall mean error of 62.5N is indicative of favorable results obtainable through biomechanics cinematography. The value of 62.5N is representative of an error within the mid-support phase between 3% and 6%, dependent on the magnitude of the force reading. This suggests that the technique described within this study for the mid-support phase calculations proved to be acceptable.

4. Takeoff phase:

When various techniques were tried in an attempt to reproduce the takeoff phase of the force-time curve in jogging, the technique of using the TOPP-1 and TOPP-2 method was determined to be most satisfactory. Since the purpose of this study was to develop a method for calculating vertical force components of jogging

utilizing biomechanics cinematography data only, the method of calculation determined to be most precise was utilized. The error of 27.9N within the entire takeoff phase, which accommodated up to 57% of the time for the entire support phase, was deemed acceptable as well, in particular since it exceeds the precision of conventional biomechanics cinematography figures during the mid-support phase (27.9N vs. 62.5N)

5. <u>Biomechanics cinematography vs force platform:</u> Upon comparison of the final measurements from the force platform with the calculations from cinematography data, a mean error of 6.2N was found over all subjects and measurements. The error of 6.2N represented the average error per measurement when taking into account all measurements for all subjects. Biomechanics cinematography therefore seems to be an acceptable technique for the calculation of vertical force parameters. Within cinematographical analysis there is always an error but if the error can be minimized, as was the case in this study, the procedure for vertical force data collection and analysis from cinematographical data can become a viable tool for the researcher and practitioner.

CHAPTER V

SUMMARY, CONCLUSION AND RECOMMENDATIONS

The purpose of this study was to develop a method for the calculation of the vertical force component of jogging through biomechanics cinematography. In particular, an attempt was made to reproduce the vertical force characteristics recorded by a force plate during jogging using cinematographical procedures. Synchronized records from cinematography of joggers in the sagittal plane and the analog force signal from a force platform were obtained.

Analysis of the direct force measurements were made using a PCB208A04 piezoelectric force transducer mounted in a force platform. When plotted graphically the force-time curves depicted the support phase of jogging. Two 16mm pin registered Photo Sonics 1PL cameras were used for the acquisition of cinematographic data. A Triad VR/100 pin registered film analyzer, Bendix Digitizing Board, and Hewlett Packard 9825B desk top computer were used for the analysis of acquired cinematographic records of the joggers. The cinematographic results were computed in three steps; the foot strike or impact phase, the mid-support phase, and the takeoff phase.

Results obtained indicated the total elapsed time for the support phase in jogging to have a mean value of 0.21 seconds. From direct force measurements, it was determined that the force-time curve has an initial peak, of short time duration, with a maximum measurement between 3.3 and 4.0 times the body weight of the subject. The initial peak was followed by a second peak which gradually descended to a force value of zero. The biomechanics cinematography procedures produced a force-time curve with similiar characteristics. It was determined that within the foot strike, mid-support, and takeoff phases, the cinematographical measurements differed from the force plate measurements by +100.7N, -62.5N, and +27.9N respectively. The magnitude of the overall mean error was found to be 6.2N.

Conclusion

Within the limitations of this study it was concluded that by adjusting conventional biomechanics cinematography procedures it appears to be possible to make biomechanics cinematography a practical tool for the measurement of vertical forces in jogging.

Recommendations

On the basis of the findings in this study, the results warranted the following recommendations:

1. A study is required for the validation of this procedure using a larger number of subjects.
2. Future studies are needed to combine various biomechanics cinematography stratagies for a measure of other biomechanical jogging parameters.
3. Studies are also needed to develop modified biomechanics cinematography procedures for determining vertical force characteristics of running, sprinting, and jumping.
4. A need must also be satisfied for additional studies to determine the temporal characteristics of the foot strike phase in jogging, running, sprinting, and jumping.
5. In calculating the takeoff phase in jogging, additional studies are required for determining other possible techniques for its computation.

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APPENDIX A

Computer Program for Data Digitizing and Storage
(University of Alberta Biomechanics Lab)

```
0: dsp "DATA DIGITIZING + STORAGE";wait 1500
1: dsp "DETERMINE SCALE FOR PLOT";wait 1500
2: dsp "DIGI LOWER LEFT CORNER";red 4,X,Y;2.54X→X;2.54Y→Y;beep
3: dsp "DIGI UPPER RIGHT CORNER";red 4,A,B;2.54A→A;2.54B→B;beep
4: (A-X)/29.25→r0→S;(B-Y)/15.24→r1
5: if r0>r1;r1→S
6: fxd 4;prt "SCALE  1-",1/S→S
7: dim A[20,28],B[20,28],D[27],C[20,10],Z$[21,36],K$[14,11]
8: S→D[26]
9: "HEAD + NECK"→K$[1];"TRUNK"→K$[2];"R.UPPER ARM"→K$[3]
10: "R.LOWER ARM"→K$[4];"R. HAND"→K$[5];"L.UPPER ARM"→K$[6]
11: "L.LOWER ARM"→K$[7];"L. HAND"→K$[8];"R. THIGH"→K$[9]
12: "R.LOWER LEG"→K$[10];"R. FOOT"→K$[11];"L. THIGH"→K$[12]
13: "L.LOWER LEG"→K$[13];"L. FOOT"→K$[14]
14: dsp "DIGITIZE USER DEFINED POINT 1";red 4,X,Y;wait 50;beep
15: 2.54X→D[22];2.54Y→D[23]
16: dsp "DIGITIZE USER DEFINED POINT 2";red 4,X,Y;wait 50;beep
17: 2.54X→D[24];2.54Y→D[25]
18: ent "DIGITIZE REFERENCE ? [1=YES]",r0
19: if r0=1;gsb "cfac"
20: if r0#1;ent "CORRECTIONFACTOR =",D[1]
21: ent "COMMENT,USER,KEEP TILL DATE",Z$[1]
22: 1→A;ent "NUMBER OF FRAMES ? [UP TO 20]",N
23: if N>20;dsp "MAXIMUM IS 20 FRAMES !!!";wait 2000;jmp -1
24: ent "DESCRIPTION OF FRAME",Z$[A+1]
25: if A>1;fxd 0;dsp "TIME INTERVAL FRAMES",A-1,A;wait 1500;ent "T=",D[A]
26: for B=1 to 14
27: 0→r2
28: if B=4;1→r2
29: if B=5;1→r2
30: if B=7;1→r2
31: if B=8;1→r2
32: if B=10;1→r2
33: if B=13;1→r2
34: if r2=1;gto 36
35: dsp "PROXIMAL",K$[B];red 4,X,Y;2.54X→X;2.54Y→Y;beep;wait 300
36: if r2=1;E→X;F→Y
37: X→A[A,B];Y→A[A,B+14]
38: dsp "DISTAL",K$[B];red 4,E,F;2.54E→E;2.54F→F;beep;wait 300
39: E→B[A,B];F→B[A,B+14]
40: next B
41: for L=1 to 5
42: dsp "DIGITIZE IMPLEMENT POINT #",L;red 4,X,Y;wait 50;beep
43: 2.54X→C[A,L];2.54Y→C[A,L+5]
44: next L
45: ent "ERROR ?? [1=YES]",r0
46: if r0=1;dsp "DIGITIZE FRAME AGAIN";wait 3000;gto 26
47: 1+A→A;if A<=N;gto 24
48: gsb "store"
49: dsp "STORAGE DONE";end
50: "cfac":
```

```
51: dsp "DIGITIZE POINT 1";red 4,X,Y;wait 100;2.54X→X;2.54Y→Y;beep
52: dsp "DIGITIZE POINT 2";red 4,K,L;wait 100;2.54K→K;2.54L→L;beep
53: ent "REAL SIZE OF REFERENCE [cm]",O
54: fxd 2;prt "Cfator",O/√((K-X)^2+(L-Y)^2)→D[1]
55: ret
56: "store":
57: N→D[27]
58: ent "FILENUMBER TO BE RECORDED ?",Q
59: ent "TRACK #",r0;trk r0
60: rcf Q,A[*],B[*],D[*]
61: rcf Q+1,Z$,K$
62: rcf Q+2,C[*]
63: trk 0
64: wtb 7,10,10,10,10,10,10,13
65: fmt ,9x,18"*",x,c20,x,17"*",/,/
66: wrt 7,"FILE CONTENTS RECORD"
67: fmt 1,9x,c10,c36,c8,f2.0
68: wrt 7.1,"DATA SPEC:",Z$[1],"IN FILE",Q
69: wtb 7,10,10,13
70: fmt 2,9x,c7,f3.0,c46,/
71: for J=1 to D[27]
72: wrt 7.2,"FRAME #",J,Z$[J+1]
73: next J
74: fmt 3,/,/,9x,c10;wrt 7.3,"COMMENTS :"
75: wtb 7,12
76: ret
*12288
```

APPENDIX B

Computer Program for Raw Data Retrieval
(University of Alberta Biomechanics Lab)

```
0: dsp "RAW DATA  RETRIEVAL";wait 1500
1: ent "FILE # TO BE RETRIEVED",Q
2: dim A[20,28],B[20,28],D[27],Z$[21,36],K$[14,11]
3: ent "TRACK #",r0;trk r0
4: ldf Q,A[*],B[*],D[*]
5: ldf Q+1,Z$,K$
6: trk 0
7: wtb 7,13,10,10,10,10,10,10
8: fmt 1,14x,c50,/;fmt 2,14x,c17,f7.4,/;fmt 3,14x,10f7.3
9: fmt 6,14x,18"*",x,c24,x,f2.0,x,18"*",/,/
10: wrt 7.6,"DATA RETRIEVAL SUBJECT #",Q
11: fmt 14x,c65,/;fmt 5,14x,65"*",/;wrt 7.5
12: wrt 7.1,Z$[1];wrt 7.5
13: wrt 7.2,"Correctionfactor=",D[1]
14: wrt 7.1,"Time Interval between the Frames (sec.)         "
15: fmt 4,9x,10f7.0;wrt 7.4,1,2,3,4,5,6,7,8,9,10
16: wrt 7.3,D[2],D[3],D[4],D[5],D[6],D[7],D[8],D[9],D[10];wtb 7,10
17: wrt 7.4,10,11,12,13,14,15,16,17,18,19
18: wrt 7.3,D[11],D[12],D[13],D[14],D[15],D[16],D[17],D[18],D[19];wtb 7,10
19: fmt 7,37x,2f7.0;wrt 7.7,19,20
20: fmt 8,42x,f7.3;wrt 7.8,D[20]
21: fmt 6,/,14x,65"-",2/;wrt 7.6
22: wtb 7,12;0→r0
23: for A=1 to D[27]
24: gsb "printout"
25: if A=D[27];wtb 7,12;dsp "RAWDATA OUTPUT DONE";end
26: next A
27: "printout":
28: if r0=2;0→r0;wtb 7,12
29: wtb 7,13,10,10,10,10,10,10
30: fmt 1,10x,7c9;fmt 2,/;fmt 3,9x,7f9.2;fmt 4,/,10x,c63
31: fmt 5,14x,c16,x,f2.0;wrt 7.5,"RAW DATA FRAME #",A
32: wrt 7.4,Z$[A+1];wrt 7.2
33: wrt 7.1,"HNeck","Trunk","RUarm","RLarm","Rhand","LUarm","LLarm"
34: wrt 7.5,"PROX.  ENDPOINTS"
35: wrt 7.3,"X",A[A,1],A[A,2],A[A,3],A[A,4],A[A,5],A[A,6],A[A,7]
36: wrt 7.3,"Y",A[A,15],A[A,16],A[A,17],A[A,18],A[A,19],A[A,20],A[A,21]
37: wrt 7.5,"DISTAL ENDPOINTS"
38: wrt 7.3,"X",B[A,1],B[A,2],B[A,3],B[A,4],B[A,5],B[A,6],B[A,7]
39: wrt 7.3,"Y",B[A,15],B[A,16],B[A,17],B[A,18],B[A,19],B[A,20],B[A,21]
40: wrt 7.2
41: wrt 7.1,"Lhand","RUleg","RLleg","Rfoot","LUleg","LLleg","Lfoot"
42: wrt 7.5,"PROX.  ENDPOINTS"
43: wrt 7.3,"X",A[A,8],A[A,9],A[A,10],A[A,11],A[A,12],A[A,13],A[A,14]
44: wrt 7.3,"Y",A[A,22],A[A,23],A[A,24],A[A,25],A[A,26],A[A,27],A[A,28]
45: wrt 7.5,"DISTAL ENDPOINTS"
46: wrt 7.3,"X",B[A,8],B[A,9],B[A,10],B[A,11],B[A,12],B[A,13],B[A,14]
47: wrt 7.3,"Y",B[A,22],B[A,23],B[A,24],B[A,25],B[A,26],B[A,27],B[A,28]
48: r0+1→r0
49: ret
*1746
```

APPENDIX C

Computer Program for Center of Mass Displacement and Velocity
(Modified from University of Alberta Biomechanics Lab)

```
0: dsp "CM [X,Y,DIPLACEMENT,VELOCITY]";wait 1500
1: dim A[20,28],B[20,28],D[27],S[14],M[14],Z[2,40],V[3,39],Z$[3,1]
2: dim K$[1,50]
3: "."→Z$[1];","→Z$[2];"*"→Z$[3]
4: ent "MALE=1,FEMALE=2",r3
5: .5→S[1]→S[2];.436→S[3]→S[6];.43→S[4]→S[7];.28→S[5]→S[8]
6: .433→S[9]→S[10]→S[12]→S[13];.45→S[11]→S[14]
7: if r3=1;jmp 2
8: if r3=2;jmp 3
9: .096→M[1];.458→M[2];.033→M[3]→M[6];.019→M[4]→M[7];.0065→M[5]→M[8]
10: .105→M[9]→M[12];.045→M[10]→M[13];.0145→M[11]→M[14];gto 13
11: .077→M[1];.463→M[2];.03→M[3]→M[6];.0155→M[4]→M[7];.005→M[5]→M[8]
12: .115→M[9]→M[12];.0525→M[10]→M[13];.012→M[11]→M[14]
13: ent "FILE # TO BE USED ?",Q
14: trk 0
15: ldf Q,A[*],B[*],D[*]
16: trk 0
17: wtb 7,12,10,10,10,10,10,10,13
18: fmt 4,10x,65"+",/;wrt 7.4;fmt 5,20x,c44,f2.0,/
19: wrt 7.5,"CENTER OF MASS DETERMINATION FOR SUBJECT # ",Q;wrt 7.4
20: wtb 7,10,10
21: fmt ,10x,c8,c14,c17,3x,c17;fmt 1,15x,2c7,4x,2c6,x,c6,4x,2c6,x,c6,/
22: wrt 7,"FRAME#  ","CM COORDINATES","DISPLACEMENT","VELOCITY"
23: wrt 7.1,"X","Y","Hor.","Ver.","LIN.","Hor.","Ver.","LIN."
24: for H=1 to D[27];0→T→U
25: D[H+1]+r14→r14
26: for I=1 to 14
27: A[H,I]-B[H,I]→O;abs(O)→O;A[H,I+14]-B[H,I+14]→P;abs(P)→P
28: S[I]O→K;S[I]P→L
29: if A[H,I]<B[H,I];K+A[H,I]→E;gto 31
30: A[H,I]-K→E
31: if A[H,I+14]<B[H,I+14];L+A[H,I+14]→F;gto 33
32: A[H,I+14]-L→F
33: M[I]E→C;M[I]F→D;C+T→R;D+U→Q;R→T;Q→U
34: next I
35: R→Z[1,H];Q→Z[2,H];if H=1;R→r7
36: if R>r7;R→r7
37: if Q>r7;Q→r7
38: if H>1;gsb "cmout"
39: fmt 2,10x,f2.0,6x,2f6.2;wrt 7.2,H,R,Q
40: next H
41: wtb 7,12;gsb "plot"
42: wtb 7,27,65,int(0/64),int(0),int(320/64),int(320)
43: fmt 6,10x,c6,f3.0,c1,c55,/,/,/;ent "FIGURE #",r16;ent "PLOT TITLE",K$[1]
44: wrt 7.6,"FIGURE",r16,":",K$[1]
45: fmt ,7x,c50,/;wrt 7,"PLOT OF VELOCITY OF CM [.=Vhor][,=Vver][*=VLIN]"
46: fmt 2,10x,c19,x,f6.3,c6
47: wrt 7.2,"ON THE Y AXIS 1 cm=",1/(B/37.8),"m/s"
48: wrt 7.2,"ON THE X AXIS 1 cm=",1/(A/47.2),"sec"
49: wtb 7,27,65,int(120/64),int(120),int(347/64),int(347)
50: K-37.8→L;0→P;fmt 3,f5.2,c1
51: for M=1 to 15
52: L+37.8→L;if L>960;gto 57
53: wtb 7,27,65,int(120/64),int(120),int(L/64),int(L)
54: wrt 7.3,P,"-"
55: 1/(B/37.8)+P→P
```

```
56: next M
57: wtb 7,27,65,int(160/64),int(160),int(370/64),int(370)
58: 155→L;0→P;fmt 4,f4.2
59: for M=1 to 7
60: L+94.4→L
61: wtb 7,27,65,int(L/64),int(L),int(370/64),int(370)
62: 1/(A/94.4)+P→P;wrt 7.4,P
63: next M
64: wtb 7,27,65,int(180/64),int(180),int(385/64),int(385);180→O
65: for M=1 to 15
66: wtb 7,27,65,int(O/64),int(O),int(385/64),int(385)
67: fmt 1,c1;wrt 7.1,"|";O+47.2→O
68: next M
69: wtb 7,12;dsp "PLOT  AND CM DONE";end
70: "cmout":
71: (Z[1,H]-Z[1,H-1])D[1]/100→r1
72: (Z[2,H]-Z[2,H-1])D[1]/100→r2
73: √(r1^2+r2^2)→r3;r1/D[H]→r4;r2/D[H]→r5;r3/D[H]→r6
74: r4→V[1,H-1];r5→V[2,H-1];r6→V[3,H-1]
75: if H=2;r4→r8→r9
76: if r4>r8;r4→r8
77: if r4<r9;r4→r9
78: if r5>r8;r5→r8
79: if r5<r9;r5→r9
80: if r6>r8;r6→r8
81: if r6<r9;r6→r9
82: fmt 4,33x,2f6.2,x,f6.2,4x,2f6.2,x,f6.2;wrt 7.4,r1,r2,r3,r4,r5,r6
83: ret
84: "plot":
85: if r9>0;0→r9
86: wtb 7,27,65,int(120/64),int(120),int(970/64),int(970)
87: fmt 8,c14;wrt 7.8,"VELOCITY (m/s)"
88: D[2]/2→r13;720/r14→A;567/(abs(r8)+abs(r9))→B
89: wtb 7,27,65,int(180/64),int(180),int(960/64),int(960)
90: wtb 7,27,46,"|",int(10/64),int(10),0
91: wtb 7,27,97,int(180/64),int(180),int(384/64),int(384)
92: 384+abs(r9)B→K
93: wtb 7,27,65,int(180/64),int(180),int(K/64),int(K)
94: wtb 7,27,46,char(95),int(30/64),int(30),9
95: wtb 7,27,97,int(900/64),int(900),int(K/64),int(K)
96: wtb 7,27,46,char(95),int(10/64),int(10),9
97: wtb 7,27,65,int(180/64),int(180),int(384/64),int(384)
98: wtb 7,27,97,int(900/64),int(900),int(384/64),int(384)
99: fmt 2,c7;wrt 7.2,"TIME(s)"
100: for S=1 to 3
101: D[2]/2→r13;0→r15;K+V[S,1]B→Y;180+r13A→X
102: wtb 7,27,65,int(X/64),int(X),int(Y/64),int(Y);wtb 7,"o",8
103: wtb 7,27,46,Z$[S],int(5/64),int(5),0
104: for C=2 to D[27]-1
105: D[C]+r15→r15
106: D[C+1]/2+r15→r13
107: K+V[S,C]B→Y;180+r13A→X
108: wtb 7,27,97,int(X/64),int(X),int(Y/64),int(Y);wtb 7,"o",8
109: next C
110: next S
111: ret
*14975
```

APPENDIX D

Computer Program for Plotting Routines
(University of Alberta Biomechanics Lab)

```
0: % "PROGRAM FOR MULTIPLE PLOTS"
1: ent "# OF Y VARIABLES",P;P→r10;ent "# OF MEASUREMENTS",Q;Q→F
2: dim Y[P,Q];dim X[Q]
3: ent "CONSTANT X INTERVAL? [1=YES]",r1
4: if r1=1;ent "X START",X;ent "X INCREMENT",r0;X→X[1];fxd 2
5: for A=1 to P
6: fxd 0;prt "Y VARIABLE",A;fxd 2;spc
7: for B=1 to Q
8: if A=1 and B>1 and r1=1;X+r0→X→X[B]
9: if A=1 and r1≠1;beep;ent X[B];prt " X",X[B]
10: ent Y[A,B];prt Y[A,B]
11: next B
12: spc
13: next A
14: ent "CHANGES ??? [1=YES]",T;if T≠1;jmp 2
15: ent "VARIABLE #",A;ent "MEASUREMENT",B;ent "NEW VALUE",C;C→Y[A,B];jmp -1
16: dim O$[1],N$[2,20]
17: ent "NAME OF Y VARIABLE",N$[1]
18: ent "NAME OF X VARIABLE",N$[2]
19: gsb "PLOT"
20: end
21: "PLOT":
22: min(X[*])→r1;max(X[*])→r0;min(Y[*])→r3;max(Y[*])→r2
23: gsb "PMIN"
24: ent "MIN Y",r3;ent "MAX Y",r2;ent "MAX X",r0;ent "MIN X",r1
25: gsb "PMIN"
26: if r1<0 and r0>0;r0+abs(r1)→r5
27: if r1>0;r0-r1→r5
28: if r1=0;r0→r5;300→X
29: if r3<0 and r2>0;r2+abs(r3)→r6
30: if r3>0;r2-r3→r6
31: if r3=0;r2→r6;450→Y
32: ent "LENGTH OF X  AXIS [cm]",r11
33: ent "LENGTH OF Y AXIS [cm]",r12
34: 47.2r11→r11;37.8r12→r12;r11/47.2r5→r13;r12/37.8r6→r14
35: if r1<0;300+abs(47.2r1r13)→X
36: if r3<0;450+abs(37.8r3r14)→Y
37: if r1>=0;300→X
38: if r3>=0;450→Y
39: wtb 7,27,79,int(X/64),int(X),int(Y/64),int(Y)
40: r0r13*47.2→O;r1r13*47.2→P;r2r14*37.8→Q;r3r14*37.8→R
41: if r1>=0;0→P;O-47.2r1r13→O
42: if r3>=0;0→R;Q-37.8r3r14→Q
43: wtb 7,27,46,"|",int(10/64),int(10),0
44: wtb 7,27,65,int(0/64),int(0),int(Q/64),int(Q);if flg1;cfg 1;jmp 2
45: wtb 7,27,10,8,8,8,8,8,8;wrt 7,N$[1];sfg 1;jmp -1
46: wtb 7,27,97,int(0/64),int(0),int(R/64),int(R)
47: wtb 7,27,46,char(95),int(10/64),int(10),9
48: wtb 7,27,65,int(P/64),int(P),int(0/64),int(0)
49: wtb 7,27,97,int(O/64),int(O),int(0/64),int(0);wrt 7,"  ",N$[2]
```

```
50: for A=1 to r10
51: for B=1 to F
52: Y[A,B]37.8r14→Y[A,B]
53: if r3>0;Y[A,B]-37.8r3r14→Y[A,B]
54: if A=1;X[B]47.2r13→X[B]
55: if A=1 and r1>0;X[B]-47.2r1r13→X[B]
56: next B
57: next A
58: for A=1 to r10
59: ent "NEXT POINT TO PLOT= [0=STOP]",A
60: if A=0 or A>r10;gto 76
61: ent "PLOTCHARACTER=",O$[1]
62: ent "PLOTDENSITY =",U
63: wtb 7,27,46,O$[1],int(U/64),int(U),0
64: wtb 7,27,65,int(X[1]/64),int(X[1]),int(Y[A,1]/64),int(Y[A,1])
65: for B=2 to F
66: wtb 7,27,97,int(X[B]/64),int(X[B]),int(Y[A,B]/64),int(Y[A,B])
67: next B
68: fxd 0;fmt 3,8x,c;wrt 16.3,O$[1];prt " PD",U;prt " P#",A;spc 2
69: next A
70: ent "MIN. Y LABEL",r16;ent "MAX. Y LABEL",r17;ent "Y LABEL INCREMENT",r18
71: if X#300 or Y#450;gsb "XY"
72: fmt ,f7.2,c;37.8r14r16→L;r16→K
73: if r3>0;L-37.8r3r14→L
74: wtb 7,27,65,int(-(104-P)/64),int(-(104-P)),int(L/64),int(L)
75: wrt 7,K," -";K+r18→K;L+37.8r14r18→L
76: if K<=r17;jmp -2
77: ent "MIN X LABEL",r16;ent "MAX X LABEL",r17;ent "X LABEL INCREMENT",r18
78: fmt ,f5.2;47.2r13r16→L;r16→K
79: if r1>0;L-47.2r1r13→L
80: wtb 7,27,65,int(L/64),int(L),int(R/64),int(R);wrt 7,"|"
81: wtb 7,27,65,int((L-24)/64),int(L-24),int(-(20-R)/64),int(-(20-R))
82: wrt 7,K;K+r18→K;L+47.2r13r18→L
83: if K<=r17;jmp -3
84: wtb 7,27,65,int(P/64),int(P),int((R-50)/64),int(R-50)
85: dim C$[1,66];1→N;ent "TITLE",C$[N]
86: fmt ,c;wrt 7,C$[N]
87: ret
88: "XY":
89: wtb 7,27,65,int(P/64),int(P),int(Q/64),int(Q)
90: wtb 7,27,46,"|",int(10/64),int(10),0
91: wtb 7,27,97,int(P/64),int(P),int(R/64),int(R)
92: wtb 7,27,46,char(95),int(10/64),int(10),9
93: wtb 7,27,97,int(O/64),int(O),int(R/64),int(R)
94: ret
95: "PMIN":
96: prt " MIN Y",r3;prt " MAX Y",r2;prt " MIN X",r1;prt " MAX X",r0;spc
97: ret
*31954
```

APPENDIX E

Computer Program for Data Analysis and Storage from Oscilloscope

```
0: dsp "DATA STORAGE FROM SCOPE";wait 2000
1: dim C$[1,20],P[35]
2: ent "COMMENT",C$[1]
3: fmt 2,10x,60"*",/
4: fmt 3,23x,c33,/
5: fmt 1,15x,c5,7x,c7,10x,c5,7x,c7,/
6: fmt 4,16x,f2.0,9x,f7.2,11x,f2.0,9x,f7.2,/
7: fmt 5,50x,c20,/,/
8: dsp "SET ORIGIN AND ZERO TOGETHER";red 4,X,Y;2.54X→X;2.54Y→Y;beep
9: dsp "DIGITIZE POINT FOR BODY WEIGHT";red 4,A,B;2.54A→A;2.54B→B;beep
10: ent "BODY WEIGHT IN KILOGRAMS",N
11: ent "NUMBER OF FRAMES TO BE DIGITIZED",K
12: (B-Y)/N→M
13: for J=1 to K
14: ent "IS SCOPE AT ZERO POINT (0=YES)",r0
15: if r0=0;0→P[J]
16: if r0>0;gto 19
17: if J=K;gto 23
18: next J
19: dsp "DIGITIZE LINE";red 4,C,D;2.54C→C;2.54D→D;beep
20: D/M→T;9.81T→P[J]
21: if J=K;jmp 2
22: next J
23: dsp "DIGITIZING DONE";wait 3000;gto 24
24: wtb 7,10
25: wrt 7.2
26: wrt 7.3,"VERTICAL FORCE FROM OSCILLOSCOPE"
27: wrt 7.2
28: wrt 7.5,C$[1]
29: wrt 7.1,"FRAME","V-FORCE","FRAME","V-FORCE"
30: for J=1 to 17
31: wrt 7.4,J,P[J],J+18,P[J+18]
32: next J
33: wrt 7.4,18,P[18]
34: wtb 7,12
35: ent "FILE NUMBER TO BE RECORDED",Q
36: trk 1
37: rcf Q,C$,P[*]
38: end
*2720
```

APPENDIX F

Computer Program for Vertical Force from Cinematography

```
0: dsp "V-FORCE FROM CINEMATOGRAPHY";wait 2000
1: dim V[35],A[35],F[35],C$[1,20]
2: ent "MASS OF SUBJECT IN KILOGRAMS",M
3: ent "TIME INTERVAL BETWEEN FRAMES",T
4: ent "NUMBER OF FRAMES",K;K-1→K
5: ent "COMMENT",C$[1]
6: for I=1 to K
7: ent "NEXT VELOCITY",V[I];beep
8: next I
9: for I=1 to K-1
10: (V[I+1]-V[I])/T→A[I]
11: MA[I]+9.8M→F[I]
12: next I
13: fmt 1,10x,60"*",/
14: fmt 2,23x,c34,/
15: fmt 3,50x,c20,/
16: fmt 4,10x,c6,f5.1,/,/
17: fmt 5,20x,c5,12x,c6,10x,c7,/,/
18: fmt 6,22x,f2.0,12x,f7.2,10x,f8.2,/
19: fmt 7,22x,f2.0
20: wrt 7.1
21: wrt 7.2,"VERTICAL FORCE FROM CINEMATOGRAPHY"
22: wrt 7.1
23: wrt 7.3,C$[1]
24: wrt 7.4,"MASS =",M
25: wrt 7.5,"FRAME","V-ACCL","V-FORCE"
26: wrt 7.7," 1";wtb 7,10
27: for I=2 to K
28: wrt 7.6,I,A[I-1],F[I-1]
29: if I=18;wtb 7,12;wrt 7.5,"FRAME","V-ACCL","V-FORCE"
30: next I
31: wrt 7.7,K+1
32: wtb 7,12
33: end
*13779
```

APPENDIX G

Center of Mass Determination for Subject EU-1

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CENTER OF MASS DETERMINATION FOR SUBJECT EU-1

++

FRAME#	CM COORDINATES		DISPLACEMENT			VELOCITY		
	X	Y	Hor.	Ver.	LIN.	Hor.	Ver.	LIN.
1	32.31	32.17						
			0.11	-0.02	0.11	3.66	-0.55	3.70
2	35.41	31.70						
			0.11	-0.01	0.11	3.75	-0.49	3.79
3	38.58	31.28						
			0.11	-0.02	0.11	3.60	-0.56	3.65
4	41.62	30.81						
			0.10	-0.01	0.10	3.45	-0.22	3.46
5	44.54	30.62						
			0.11	0.01	0.11	3.73	0.44	3.76
6	47.70	31.00						
			0.11	0.02	0.11	3.70	0.75	3.78
7	50.83	31.63						
			0.11	0.02	0.12	3.79	0.67	3.85
8	54.03	32.20						
			0.11	0.01	0.11	3.52	0.46	3.55
9	57.01	32.59						
			0.11	0.01	0.11	3.71	0.47	3.74
10	60.15	32.98						

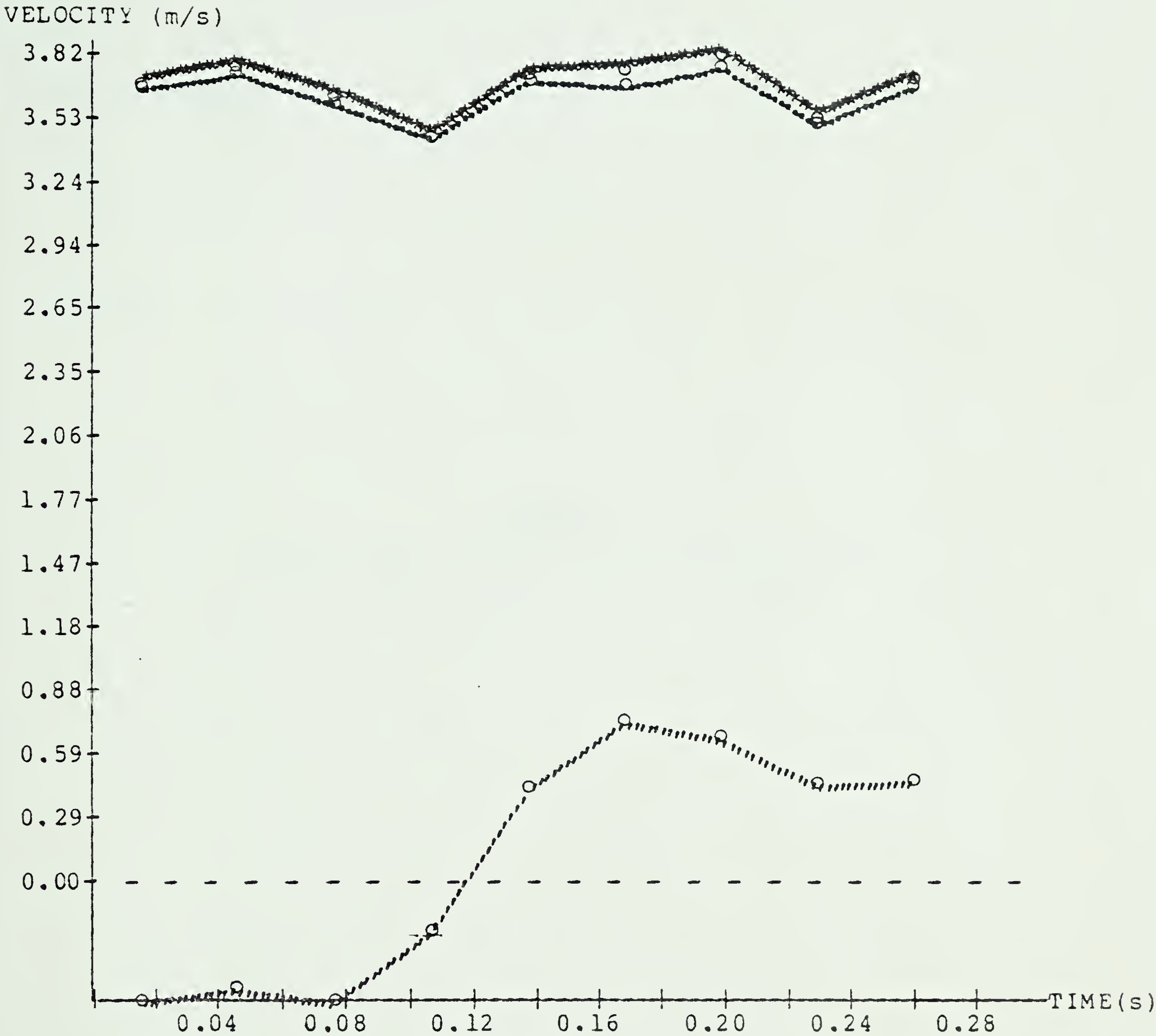

FIGURE 13: Subject EU-1

PLOT OF VELOCITY OF CM [.=Vhor][,=Vver][*=VLIN]

ON THE Y AXIS 1 cm= 0.294 m/s
ON THE X AXIS 1 cm= 0.020 sec

APPENDIX H

Center of Mass Determination for Subject JT-2

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CENTER OF MASS DETERMINATION FOR SUBJECT JT-2

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FRAME#	CM COORDINATES		DISPLACEMENT			VELOCITY		
	X	Y	Hor.	Ver.	LIN.	Hor.	Ver.	LIN.
1	35.24	37.71						
			0.10	-0.03	0.10	3.23	-0.96	3.37
2	37.97	36.90						
			0.09	-0.02	0.10	3.14	-0.73	3.22
3	40.63	36.28						
			0.11	-0.01	0.11	3.61	-0.39	3.64
4	43.68	35.95						
			0.09	0.01	0.09	3.14	0.27	3.15
5	46.34	36.18						
			0.10	0.02	0.10	3.37	0.80	3.46
6	49.18	36.86						
			0.10	0.02	0.11	3.47	0.78	3.55
7	52.12	37.51						
			0.10	0.02	0.11	3.50	0.61	3.55
8	55.07	38.03						
			0.09	0.01	0.09	3.09	0.34	3.11
9	57.68	38.31						

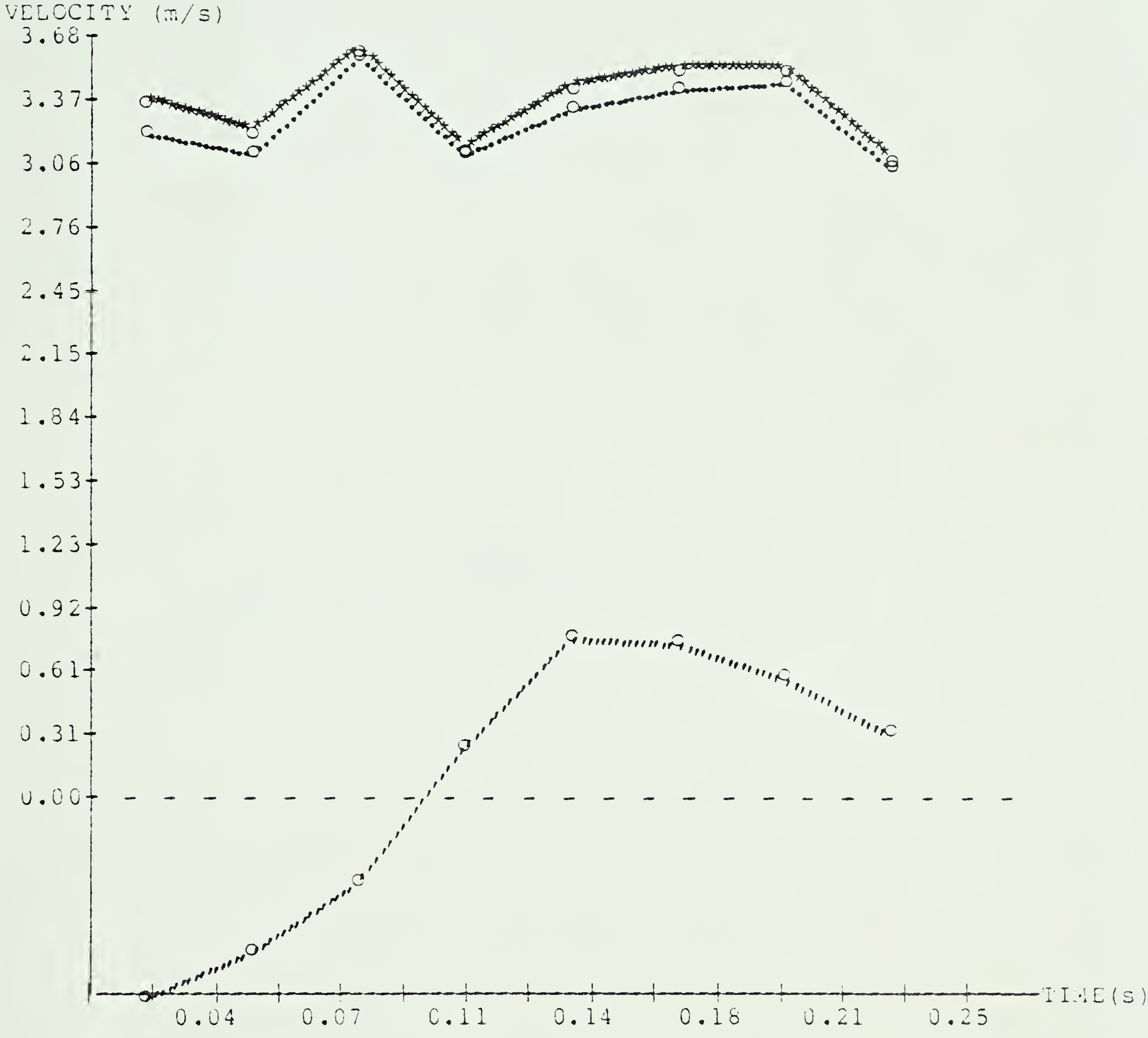

FIGURE 14: Subject JT-2

PLOT OF VELOCITY OF CM [.=Vhor][,=Vver][*=VLIN]

ON THE Y AXIS 1 cm= 0.306 m/s
ON THE X AXIS 1 cm= 0.018 sec

APPENDIX J

Center of Mass Determination for Subject GS-3

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CENTER OF MASS DETERMINATION FOR SUBJECT GS-3

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FRAME#	CM COORDINATES		DISPLACEMENT			VELOCITY		
	X	Y	Hor.	Ver.	LIN.	Hor.	Ver.	LIN.
1	34.11	36.13						
			0.11	-0.02	0.11	3.59	-0.82	3.69
2	37.14	35.44						
			0.11	-0.03	0.12	3.80	-1.01	3.94
3	40.36	34.58						
			0.10	-0.01	0.10	3.18	-0.24	3.19
4	43.04	34.38						
			0.11	0.01	0.11	3.56	0.39	3.59
5	46.06	34.71						
			0.09	0.02	0.10	3.16	0.73	3.24
6	48.73	35.32						
			0.10	0.03	0.11	3.47	1.11	3.64
7	51.66	36.26						
			0.10	0.03	0.11	3.40	0.89	3.51
8	54.53	37.01						
			0.11	0.02	0.12	3.77	0.74	3.84
9	57.71	37.64						
			0.10	0.01	0.10	3.40	0.35	3.41
10	60.58	37.93						
			0.11	-0.00	0.11	3.51	-0.13	3.51
11	63.55	37.82						

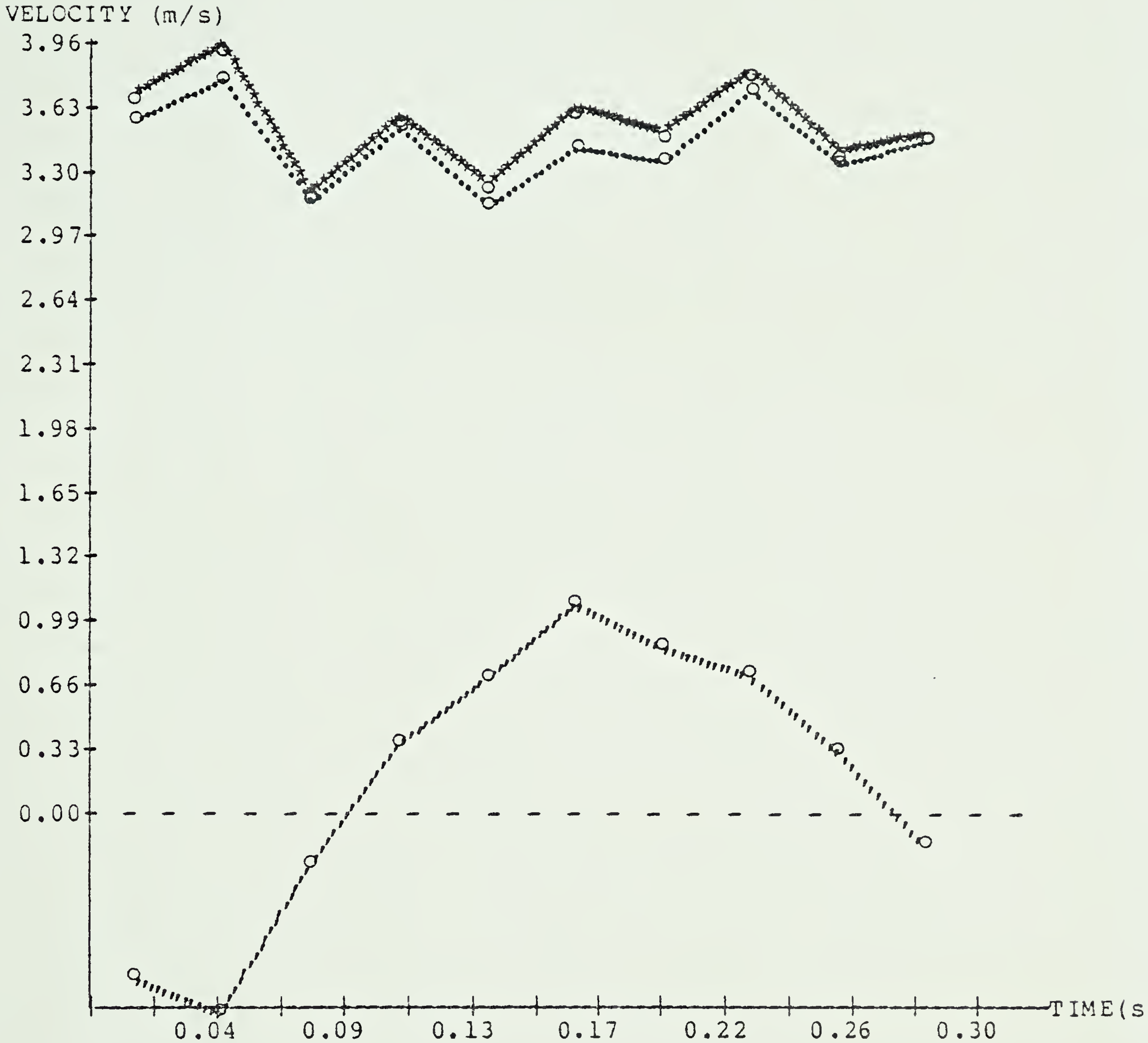

FIGURE 15: Subject GS-3

PLOT OF VELOCITY OF CM [.=Vhor][,=Vver][*=VLIN]

ON THE Y AXIS 1 cm= 0.330 m/s
ON THE X AXIS 1 cm= 0.022 sec